

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

CHARLES D. WALCOTT, DIRECTOR

T H E

RELATION OF RAINFALL TO RUN-OFF

BY

GEORGE W. RAFTER



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The publications of the United States Geological Survey consist of (1) Annual Reports; (2) Monographs; (3) Professional Papers; (4) Bulletins; (5) Mineral Resources; (6) Water-Supply and Irrigation Papers; (7) Topographic Atlas of United States, folios and separate sheets thereof; (8) Geologic Atlas of United States, folios thereof. The classes numbered 2, 7, and 8 are sold at cost of publication; the others are distributed free. A circular giving complete lists may be had on application.

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(Continued on third page of cover.)

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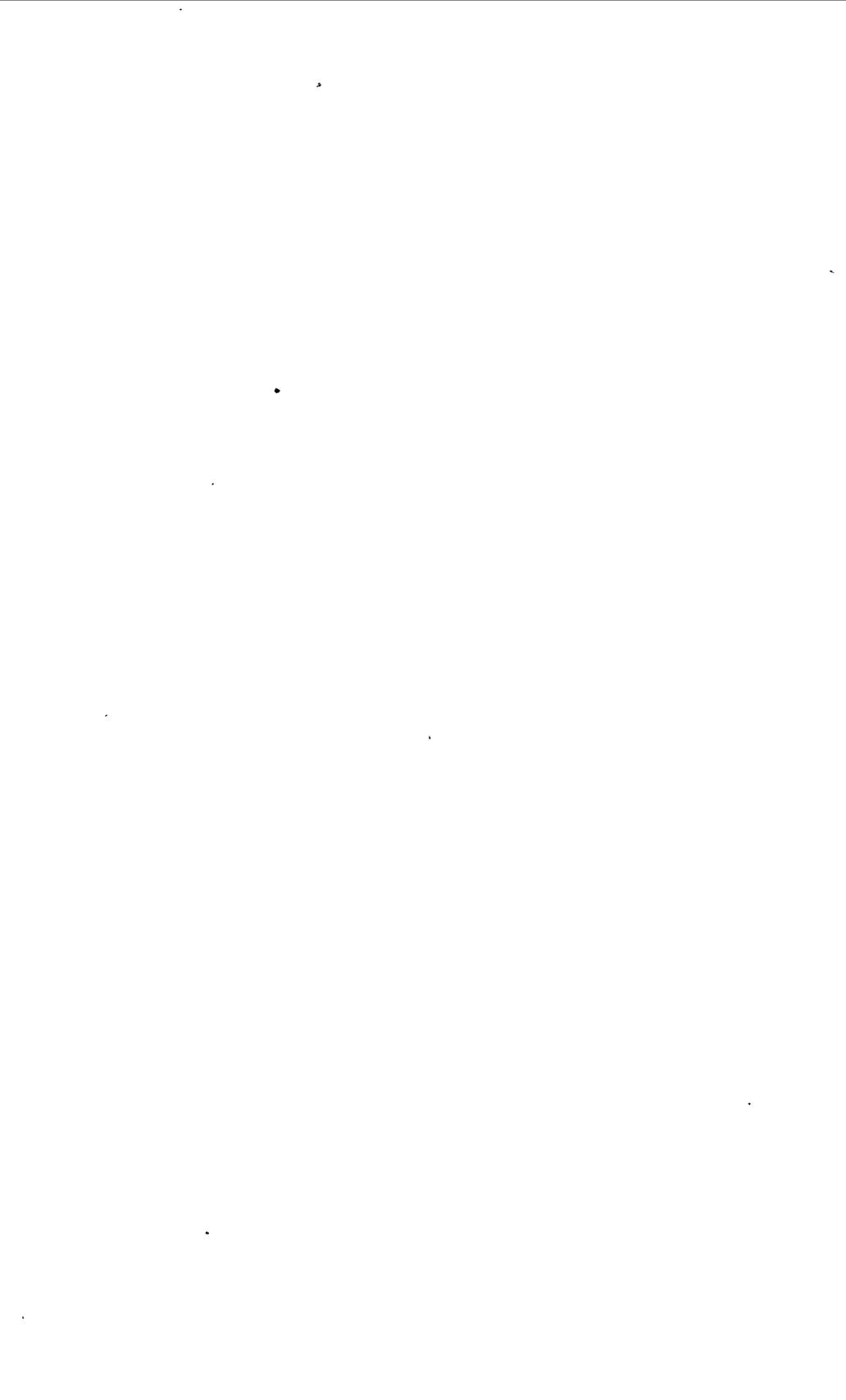
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THE RELATION OF RAINFALL TO RUN-OFF.

By GEORGE W. RAFTER.

INTRODUCTION.

The run-off of a stream is influenced by many complex conditions—as, for instance, amount of rainfall and its intensity, nature of soil, slope of surface, and area and configuration of catchment basin. It is also influenced by geologic structure, forests, wind, force of vapor pressure, and other elements. Data are still lacking for a really satisfactory discussion of the question, although they have accumulated so rapidly during the last few years that many conservative conclusions can be drawn which may be accepted as substantially true.

The subject has been discussed in the Transactions of the American Society of Civil Engineers by Messrs. Herschel, Fteley, FitzGerald, Babb, and others in a series of able papers,^a but no one of these exhibits a complete view.

It has also been discussed in other publications, but so far as known to the writer the Transactions of the American Society contain the most complete discussion of the subject that can be found in English engineering literature.

As a result of many years' study of the problem indicated by the title of this paper the writer has come to the conclusion that no general formula is likely to be found expressing accurately the relation of rainfall to the run-off of streams, for streams vary widely in their behavior, and when they do agree the agreement is usually accidental. As a general proposition we may say that every stream is a law unto itself.

The final formula of run-off for a given stream, therefore, will differ in some particulars from that for every other, except that there may be accidental resemblances as regards slope, shape of catchment area, or some other peculiarity. It is, however, true that an empirical formula may be made for certain classes of streams which will give approximately the run-off for a series of years.

^aSee Trans., Vol. X, p. 225; Vol. XXVII, p. 253; and Vol. XXVIII, p. 323.

RAINFALL.

CAUSE OF RAINFALL.

The cause of rainfall has been discussed by Mr. Velschow in the Transactions of the American Society of Civil Engineers.^a This paper may be referred to for a very good discussion of the subject.

The subject is also very ably discussed by Alfred J. Henry in one of the Weather Bureau reports.^b Mr. Henry remarks that the theories of rainfall given in books of twenty or thirty years ago are not now wholly accepted. Still there is one simple principle upon which no disagreement exists—that in order to produce rain the temperature of the air must be suddenly cooled below the dew point. When the air is thus cooled a portion of the vapor is changed to the liquid state and the particles thus formed may float away with the wind or they may increase in size and fall to the ground by virtue of gravity. Whether the condensation results simply in cloud, or whether rain falls, depends on the magnitude of the temperature changes taking place in the air mass.

The precise manner in which air is cooled to produce rain, whether by contact or by mixing, is not clearly apprehended. Cooling by expansion, as air ascends, is one of the most effective causes of rainfall. The ascensional movement is brought about in several ways, probably the most important of which is circulation of air in cyclonic storms, by a radial inflow from all sides and an ascensional movement in the center. A very large percentage of the rain of the United States is precipitated in connection with the passage of storms of this class.^c

Mr. Henry discusses the precipitation of the United States under the following topics: (1) The statistics used and their accuracy; (2) Geographic distribution and annual allowance; (3) Monthly distribution by districts and types; (4) The precipitation of the crop-growing season; (5) Secular variations; (6) Details of the precipitation by geographic districts; and (7) Excessive precipitation.

The chapter on "Excessive precipitation" is probably, from an engineering point of view, the most important. Mr. Henry states that in 1888 attention was first directed to the importance of statistics of excessive rainfall. At the present time the Monthly Weather Review publishes a table of maximum rainfalls in five and ten minute and one hour periods, etc.

Table No. VIII of Mr. Henry's paper gives details of excessive rainfall at Washington, Savannah, and St. Louis, and Table No. IX gives maximum intensity of rainfall for periods of five, ten, and sixty min-

^aThe cause of rain and the structure of the atmosphere, by Franz A. Velschow: Trans. Am. Soc. Civil Eng., Vol. XXXIII, 1890, p. 303.

^bRainfall of the United States, by Alfred J. Henry, chief of division: Ann. Rept. Weather Bureau, 1896-97, p. 317.

^cAbstracted from Mr. Henry's paper.

utes at the Weather Bureau stations equipped with self-registering gages, compiled from all available records. Inasmuch as this paper may be readily referred to in the publication cited, further detail is omitted.

MEASUREMENT OF RAINFALL.

The subject, "How close may rainfall be measured?" has been fully discussed by Prof. Cleveland Abbe.^a Professor Abbe states that the influence of altitude was first brought to the attention of the learned world by Heberden who, in 1769, in a memoir in the Transactions of the Royal Society of London, stated that a gage on Westminster Abbey, over 150 feet above the ground, caught less than half as much as a gage at the ground.

Profs. Alexander D. Bache and Joseph Henry, and Mr. Desmond FitzGerald have studied the question extensively in this country. Mr. FitzGerald's results may be found in the Journal of the Association of Engineering Societies for August, 1884.^b

Mr. FitzGerald kept two gages, one at a height of 2 feet 6 inches above the level of the ground, and the second at a distance of 150 feet from the first, and at an elevation of 20 feet 4 inches above the lower gage. Both gages were 14.85 inches in diameter. These gages were located at Chestnut Hill reservoir, in the city of Boston, but the observations for wind velocity were taken from the Signal Service observations, 5 miles distant. With only five exceptions during the five-year period, the upper gage delivered materially less water than the ground gage, the average difference being 10.6 per cent for the whole period. But snowfalls and mixtures of snow and rain are not included in the table of data given in the paper.

The results recorded by Professor Abbe are somewhat more extensive than those presented by Mr. FitzGerald, though Mr. FitzGerald states in his paper that he has prepared a series of experiments with nine gages and a self-recording anemometer, from which in the course of time some more definite results may be reached. So far as the writer knows, this second series of observations has not been published.

In order to show how the catch of rainfall diminishes with height of the gage, Professor Abbe gives in his Table No. IV the results of observations at different places. These range from 90 per cent of a gage at the ground to 47 per cent. In Tables Nos. I, II, and III, Professor Abbe also gives the result of various gages, which gave 52 to 7 per cent less of rainfall, and from 80 to 16 per cent less of snowfall, than gages at the ground. Professor Abbe remarks that these tables show conclusively the large influence of wind on the catch of rain, but show

^aDetermination of the true amount of precipitation and its bearing on theories of forest influences, by Cleveland Abbe: Appendix I of Bulletin No. 7, Forest Influences; Forestry Division, United States Department of Agriculture.

^bDoes the wind cause the diminished amount of rain collected in elevated rain gages? By Desmond FitzGerald: Jour. Assoc. Engineering Societies, Vol. III, No. 10 (August, 1884).

nothing of its influence on the catch of snow. As an observational method of obtaining the true rainfall from gage readings, Professor Abbe suggests the following as offering a fair approximation:

If the present gage has been standing in an open field at a few feet elevation, place two or more similar gages near it, and similarly located as far as obstacles are concerned, except only that one of these is to be decidedly lower than the old one and the other decidedly higher. From a comparison of the simultaneous records of any two gages and their altitudes, we should for each separate rainfall, rather than for the monthly and annual sums, deduce the normal rainfall by the solution of two or more equations of the form:

Observe catch of gage = $(1-x \text{ altitude}) \times (\text{desired catch of normal pit gage})$. (1)

Where x is the unknown special coefficient of deficiency due to wind at that altitude—that is to say, having two gage catches, c_1 and c_2 for the two altitudes, H_1 and H_2 —we obtain the true rainfall (R) by the formulas:

$$c_1 = (1 - x\sqrt{H_1}) R; \text{ and} \quad (2)$$

$$c_2 = (1 - x\sqrt{H_2}) R. \quad (3)$$

whence,

$$R = \frac{c_1\sqrt{H_2} - c_2\sqrt{H_1}}{\sqrt{H_2} - \sqrt{H_1}} = c_1 + \frac{1}{\sqrt{\frac{H_2}{H_1}} - 1} (c_1 - c_2) = c_1 + n(c_1 - c_2). \quad (4)$$

If c_1 and H_1 relate to the lower gage, we shall generally have $c_1 > c_2$ and $H_1 < H_2$, and the coefficient n will be a positive fraction, for value of which, for such combinations as may easily occur in practice, a table is given in the paper.

It is evident then, without special discussion, that nearly all rainfall measurements thus far made in the United States are only approximations, and that while they remain in this state to carry them out to more than one decimal place is an unnecessary refinement.

DETERMINATION OF MINIMUM RAINFALL.

The writer has spent considerable time in an attempt to determine about what the minimum rainfall at any particular station may be expected to be; or, rather, he has endeavored to ascertain the relation between the minimum rainfall and the maximum. In the course of this quest he has examined practically all the records in the State of New York, as well as many records in New Jersey, Pennsylvania, Michigan, Illinois, Nebraska, Colorado, and Wyoming, as well as in Canada. As a general rule, to which there are some exceptions; the minimum rainfall may be placed at about one-half of the maximum. That is, if the maximum rainfall at a given station is about 50 inches, the minimum will be in the vicinity of 20 to 25 inches. In some cases the minimum will be not more than one-third of the maximum, or even somewhat less than one-third; occasionally, not more than one-quarter. It is not intended, however, to lay this down as an absolutely universal rule, but rather, for the present, as a somewhat imperfect guide. As a further rough guide it remains to point out that in case a given record does not conform substantially to the foregoing it may be assumed that either the minimum or the maximum,

as the case may be, is still to occur. Near the seacoast, where the supply of moisture in the air is more nearly constant, there is less variation than in the interior, and the rule that the maximum is double the minimum is more generally true. This proposition is also generally true as regards English meteorology.

IS RAINFALL INCREASING?

This question has been discussed by Prof. Mark W. Harrington,^a who, however, reached no very definite conclusion, although he is disposed to answer it in the negative. The method of discussion followed was to reduce the annual rainfalls to a series of means of each five years. These means were entered on a succession of maps, five years apart in time, and on these maps was drawn the line of 40 inches of annual rainfall. The question to be determined is, as we draw this line for each five-year mean, Does it change its position in any regular and systematic way?

An examination of the detail shows that while these lines are subject to limited fluctuations there are no uniform or systematic fluctuations. The line of equal rainfall for 1861-1865 occupied nearly the same position as the line for 1886-1890. The variations are sometimes extensive, but without systematic progress. Professor Harrington therefore concludes that with the data at hand there is not sufficient evidence of systematic fluctuation of the rainfall.

RELATION OF RAINFALL TO ALTITUDE.

This matter has been referred to in a discussion of Mr. Noble's paper on Gagings of Cedar River, Washington,^b where the statement has been made that in the State of New York the rainfall records show both increase and diminution of precipitation with increase of altitude. The Hudson River catchment area shows a higher precipitation at the mouth of the river than it does at its source in the Adirondack Mountains, while the Genesee River shows the opposite, namely, higher precipitation at its source than at its mouth.

According to a table of average monthly, annual, and seasonal precipitation in Mr. Turner's monograph on the climate of New York State^c it appears that the coast region, which includes Block Island, East Hampton, Setauket, Fort Columbus, New York City, Mount Pleasant, Tarrytown, White Plains, Croton dam, and North Salem, has an average annual precipitation of 44.93 inches. With the exception of Block Island these stations are all in New York and not far

^aRainfall and snow of the United States, compiled to the end of 1891, with annual, seasonal, monthly, and other charts, by Mark W. Harrington: Bulletin C, Weather Bureau, U. S. Dept. of Agriculture.

^bTrans. Am. Soc. Civil Eng., Vol. XLI, pp. 1-26.

^cThe climate of New York State, by E. T. Turner, C. E., late meteorologist of the New York weather bureau: Fifth Ann. Rept. New York Weather Bureau, 1893. Reprinted in Eighth Ann. Rept. of the bureau, 1896.

from the coast, and they range in elevation above tide water from 16 feet at East Hampton to 361 feet at North Salem. The average elevation of the coast region is 132 feet. The records vary in length from 7 years to 49 years, with a total of 195 years. Five of the stations are in Westchester County.

As given by Mr. Turner, the northern plateau includes Constableville, Lowville, Fairfield, Johnstown, Pottersville, Elizabethtown, Keene Valley, and Dannemora, in the counties of Lewis, Herkimer, Warren, Essex, and Clinton. According to the table the average annual precipitation at these places is 38.97 inches. The elevation of the stations above tide ranges from 600 feet at Elizabethtown to 1,356 feet at Dannemora, with an average elevation of 973 feet. The records vary in length from 4 to 22 years, with a total of 73 years.

Again, the western plateau, which includes stations in Cattaraugus, Wyoming, Allegany, Steuben, Livingston, and Chemung counties, has an average elevation above tide of 1,307 feet, ranging from 1,950 feet to 525 feet, and has an average annual precipitation of 35.58 inches, while the Hudson Valley, which includes stations in Putnam, Orange, Dutchess, Ulster, Columbia, Albany, Rensselaer, and Washington counties, has an average elevation of 230 feet above tide, with an average annual precipitation of 38.46 inches. The records range from 9 years to 65 years, with a total of 277 years.

The Great Lakes region, with an average elevation of 494 feet, has an average annual precipitation of 35.17 inches, while the central lake region, with an average elevation of 690 feet, has an average annual precipitation of 43.41 inches.

Mr. Turner's table is based on a calendar year, from January to December, inclusive. Further data may be obtained from this excellent table.

In Table No. 24 of the Upper Hudson Storage Surveys Report for 1896 there is given the mean precipitation of the Upper Hudson catchment area. The stations therein included are: Albany, 1825-1895, 71 years; Glens Falls, 1879-1895, 17 years; Keene Valley, 1879-1895, 17 years; western Massachusetts, 1887-1895, 9 years; northern plateau, 1889-1895, 6½ years; Lowville Academy, 1827-1848, 22 years; Johnstown Academy, 1828-1845, 18 years; Cambridge Academy, 1827-1839, 13 years; Fairfield Academy, 1828-1849, 22 years; Granville Academy, 1835-1849, 15 years. Assuming the northern plateau as a unit the total number of years is 199½, and the mean of all is 37.4 inches. A reference to the rainfall map in the report of the United States Board of Engineers on Deep Waterways will show that this is necessarily an approximation, because of great lack of stations in the interior of this region.

As regards the catchment area of the Upper Genesee River, there is a very decided increase in rainfall as one goes toward the source. For the years 1889-1896, inclusive, the rainfall in the upper area of this stream was 42.19 inches, while at Rochester for the same years

it was 35.64 inches. This statement is especially interesting, because there seems to be a well-marked line dividing the smaller rainfalls of the lower area from the higher rainfalls of the upper. At Hemlock Lake, Avon, and Mount Morris the rainfalls are all low, the average at Hemlock Lake from 1876-1895, inclusive, being 27.56 inches. In 1880 it was 21.99 inches; in 1879, 22.16 inches, and in 1881 only 24.36 inches. We have here three years of exceedingly low rainfall, in which the run-off must have also been very low. In 1895 the rainfall at Hemlock Lake was only 18.58 inches. The average precipitation at Avon and Mount Morris from 1891 to 1896, inclusive, was 30.12 inches. In 1895 it was only 25.05 inches. The following are stations at which it was much higher for the years 1891 to 1895, inclusive: Leroy, 45.25 inches, and Arcade, 41.60 inches.

The statements of precipitation in Genesee River catchment area are all based on a water year, December to November, inclusive.

The following are from Russell's *Meteorology*,^a illustrating Atlantic coast rainfalls, and are the averages derived from observations extending from 1870 to 1888. The rainfalls are stated to be fairly representative for large districts of country around the places.

At Jacksonville the weather bureau office is at an elevation above tide of 43 feet, while the average annual rainfall is 57.1 inches. At Norfolk the elevation of weather bureau is 57 feet above tide, and the average rainfall is 51.7 inches. At Boston the weather bureau office is 125 feet above tide, and the average rainfall is 46.8 inches.

The following illustrate the change as one goes north through the Mississippi Valley: At New Orleans the weather bureau office is 54 feet above tide, the average rainfall 62.6 inches; at St. Louis, weather bureau office 567 feet above tide, average rainfall 37.8 inches; at St. Paul, weather bureau office 850 feet above tide, average rainfall 28.9 inches.

The following illustrate the Rocky Mountain region: At Fort Grant, Ariz., elevation of weather bureau 4,833 feet, average rainfall 15.8 inches; at Denver, elevation of weather bureau 5,300 feet, average rainfall 14.7 inches; at Fort Benton, Mont., elevation 2,565 feet, average rainfall 13.2 inches.

The following illustrate the Pacific coast region: At Portland, elevation of weather bureau office is 157 feet, average rainfall 50.3 inches; San Francisco, elevation 153 feet, average rainfall 23 inches; San Diego, elevation 69 feet, average rainfall 10.2 inches.

These figures abundantly support the proposition that in the United States the rule of increased precipitation with higher altitude is by no means universal. The writer can not say positively, because he has not examined the vast number of records with reference to this point, but he thinks it quite possible that the reverse is more nearly true. That is, owing to distance from the ocean, prevailing direction

^aMeteorology, by Thomas Russell, U. S. Asst. Engineer.

of wind, and other causes, it is probable that for the entire country precipitation decreases with higher altitude rather than increases.

The decision of this question will depend to some extent upon the steepness of ascent. Thus on Mount Washington, which is projected into the air far above the surrounding mountains, the rainfall is about 83 inches. In other cases, where the ascent is gradual, no increase is apparent. The same is also frequently true of sharp ascents. On Longs Peak, in Colorado (elevation 14,271 feet), the rainfall in 1899 was 16.7 inches.

Moreover, the writer has mostly avoided comparatively small differences in rainfall—those not exceeding 2 to 2.5 inches. In such cases the difference is too small to be any certain guide. Especially is this true in the case of the northern plateau, where there is still a great lack of stations. The differences between high altitudes and low should be as much as 5 or 6 inches. Again, whether the excess rainfall occurs in the winter or summer months must be taken into account. If it occurs in the summer, even 3 inches of rainfall may not make more than 0.1 or 0.2 inch in the stream. Rainfall and run-off observations are not yet, nor are they likely to ever be, definite enough to take into account an annual difference of much less than about 1 to 1.5 inches. Again, the writer has ceased to be excessively particular about the total of the annual rainfall. Assuming some considerable length of record, small errors have relatively slight effect. This matter is referred to here because nearly all rainfall records—at any rate in the United States—have more or less error in them, and while it is desirable to have records as reliable as possible, a few errors do not affect a record very seriously. It is nevertheless very desirable to know the history of the record in order to insure the degree of confidence to be placed in it.

MAP OF AVERAGE RAINFALL IN THE STATE OF NEW YORK.

On Pl. XCVIII of the Report to the United States Board of Engineers on Deep Waterways, the writer has given the average rainfall at a large number of stations throughout the State of New York. When this map was prepared considerable time was expended in drawing lines of equal rainfall upon it, but so many discrepancies appeared that it was finally concluded, for the present, that it should be allowed to stand without such lines. The only way these contours could be drawn with any satisfaction was to omit stations which conflicted too much therewith. This, the writer did not feel justified in doing. The observations are not extensive enough to enable one to draw these lines.

DIVISION OF RAINFALL AND RUN-OFF INTO STORAGE, GROWING, AND REPLENISHING PERIODS.

The writer has found it very convenient to divide rainfall and run-off records into the three periods, those of storage, growing, and

replenishing, with a water year beginning December 1 and ending November 30. The storage period includes the months from December to May, inclusive, during which the evaporation and absorption by plants are relatively slight, and a very large proportion of the rainfall appears in the streams.

The growing period, June to August, inclusive, includes the period of active vegetation, when evaporation and absorption by plants are most notable. During this period, frequently not more than 0.1 of the rainfall appears in the streams, and sometimes not more than 0.05 or even less. Ground water tends to become lower and lower during this period, unless the rainfall is much higher than the average.

In the replenishing period, September to November, inclusive, with the normal rainfall, ground water tends to recover, and the run-off is larger than in the preceding period. This period is replenishing in this, that there is a tendency to return to normal conditions.

No hard and fast rule, however, can be laid down as to the beginning and ending of these periods. In some years the beginning of the water year should be placed at November 1, instead of December 1, while in others the storage period may end with April. Very often, one period runs into another, but after considerable study the foregoing divisions have been accepted as, on the whole, best representing all the conditions. In England many hydrologists begin the water year with September 1 as best suiting the conditions. The same thing has been done by the Philadelphia water department in tabulating the data of Neshaminy, Perkiomen, Tohickon, and Wissahickon creeks and Schuylkill River.

One great advantage of dividing records into these periods is as follows: Since evaporation and plant absorption are light during the months of the storage period, it follows to a great degree that the amount of water which can be stored is exhibited by the rainfall of the storage months. Realizing this fact, it has been the writer's habit for several years, in storage projects, to first tabulate rainfall in the manner indicated. Such procedure has the advantage that it leads one away from the contemplation of mere detail. There is a positive disadvantage in considering the monthly quantities, for which there is no compensation. The division into the three periods exhibits the more important characteristics without overburdening the mind. It is believed that a considerable advance on ordinary practice has been made by proceeding in the manner stated.

LENGTH OF TIME REQUIRED TO MAKE GOOD A SERIES OF RAINFALL RECORDS.

This question is partially answered in the writer's second report on the Upper Hudson Storage Surveys, for 1896, by a short analysis

of a paper by Alexander R. Binnie, member of the Institution of Civil Engineers.^a

One of the important problems worked out by Mr. Binnie is an answer to this question: What is the least number of years of which the continuous record, when the average rainfall has been determined, will not be materially affected, so far as the value of the mean is concerned, even if the record be extended by a greater number of years' observations? Also, What is the probable accuracy of any record the length of which is less than that necessary to give an average which will not be materially altered when the record is extended?

Space will not be taken to show Mr. Binnie's views in detail, for which reference may be made to the abstract in the second Hudson report, or, for the complete views, to the paper in the Proceedings of the Institution of Civil Engineers, but assuming that the observations are properly made it is stated that "dependence can be placed on any good record of thirty-five years' duration to give a mean rainfall correct within 2 per cent of the truth."

Further, it can be stated that for records from twenty years to thirty-five years in length, the error may be expected to vary from 3.25 per cent down to 2 per cent, and that for the shorter periods of five, ten, and fifteen years, the probable extreme deviation from the mean would be 15 per cent, 8.25 per cent, and 4.75 per cent, respectively.

A twenty years' record, therefore, may be expected to show an error of 3.24 per cent. This is about as close as rainfall records in this country can be expected to agree, as comparatively few are much beyond twenty years in length.

In his paper on the Rainfall of the United States, Mr. Henry has examined this question, using long records at New Bedford, St. Louis, Philadelphia, Cincinnati, and other places. The rainfall has been measured at New Bedford for 83 consecutive years, and at St. Louis for 60 years. For a 10-year period Mr. Henry found the following variations from the normal: At New Bedford + 16 per cent and - 11 per cent; at Cincinnati, + 20 per cent and - 17 per cent; at St. Louis, + 17 per cent and - 13 per cent; at Fort Leavenworth, + 16 per cent and - 18 per cent; and at San Francisco, + 9 per cent and - 10 per cent. For a 25-year period, it was found that the extreme variation was 10 per cent, both at St. Louis and New Bedford. Mr. Henry reached the conclusion that at least 35 to 40 years' observations are required to obtain a result that will not depart more than ± 5 per cent from the true normal. The average variation of a 35-year period was found to be ± 5 per cent, and for a 40-year period ± 3 per cent.

This preliminary study indicates slightly more range than was found

^a On mean or average rainfall and the fluctuations to which it is subject, by Alexander R. Binnie, Inst. C. E.: Proc. Inst. C. E., Vol. CIX (1892), pp. 89-172.

by Mr. Binnie, although it may be remembered that the observations of the latter are far more extensive than Mr. Henry's.

Again, since the run-off is a function of the rainfall, it follows that it must be affected in some degree in a similar manner. As to just the relation, so far as known, very few computations have been made. Indeed, very few run-off tabulations are extant which are long enough to settle this question. It is clearly, therefore, very difficult to solve definitely so abstruse a problem as that of the extent to which forests affect rainfall. All solutions are necessarily, and will be for some time to come, tentative in their character.

RUN-OFF.

THE LAWS OF STREAM FLOW.

A general statement of these laws from Mr. Vermeule is as follows:

The waters of the earth are taken up by the process which we call evaporation and formed into clouds, to be again precipitated to earth in the form of rain or snow. Of the water which falls upon the basin of a stream, a portion is evaporated directly by the sun; another large portion is taken up by plant growth and mostly transpired in vapor; still another portion, large in winter but very small in summer, finds its way over the surface directly into the stream, forming surface or flood flows; finally, another part sinks into the ground, to replenish the great reservoir from which plants are fed and stream flows maintained during the periods of slight rainfall, for the rainfall is frequently, for months together, much less than the combined demands of evaporation, plant growth, and stream flow. These demands are inexorable, and it is the ground storage which is called upon to supply them when rain fails to do so.

All of these ways of disposing of the rain which falls upon the earth may be classed as either evaporation or stream flow. Evaporation we make to include direct evaporation from the surface of the earth, or from water surfaces, and also the water taken up by vegetation, most of which is transpired as vapor, but a portion of which is taken permanently into the organisms of the plants. Stream flow includes the water which passes directly over the surface to the stream, and also that which is temporarily absorbed by the earth to be slowly discharged into the streams. A portion, usually extremely small, passes downward into the earth and appears neither as evaporation nor as stream flow. It is usually too small to be considered, and we may for our purposes assume that all of the rain which falls upon a given watershed and does not go off as stream flow is evaporated, using the latter word in the broadened sense which we have above described.

Probably one very important effect of forests is that upon the ground-water flow of streams. The stream with a catchment area wholly or largely in forests will show, without exception, a much better ground flow than one with the area denuded of forests. Neshaminy and Tohickon creeks may be cited as streams with the smallest amount of forest and the lowest curve of ground-water flow. Possibly this is not entirely due to forests, but it may be assumed that they bear some relation to the result.^a

^aExamples of ground-water curves for the chief streams herein considered may be found in Mr. Vermeule's report on the flow of streams, etc., in Final Rept. State Geologist of New Jersey, Vol. III. Trenton, 1894.

UNITS OF MEASUREMENT.

Clemens Herschel, member American Society Civil Engineers, in his paper on *Measuring Water*,^a has defined the essential elements of this question in the following terms:

For most purposes the unit of volume, when using English measures, has been agreed upon in favor of the cubic foot, and the nations of the earth being fortunately agreed upon their measures of time, have settled upon one second of time as the unit to use in measuring water. Nevertheless, the million United States gallons in twenty-four hours has become a standard for city water supply practice in the United States, and an acre in area covered an inch or a foot deep in a month or in a year is used in irrigation practice. But I would warn all engineers to be very slow to add to the number of such standards of measure for flowing water, and to abstain from and frown down such absurd standards as cubic yards per day, or tons weight of water per day, or even cubic feet per minute (instead of second), and other incongruities. * * * As exercises in the art of arithmetic for children such computations may have value, but in the work of civil engineers they become a stumbling block to an advance of knowledge, and while unduly magnifying the unessentials they indicate a deplorable lack of appreciation of the essentials of the art of the civil engineer.

Cubic measures do well enough for the contents of vessels, or as we may express it, for dealing with the science of hydrostatics. But so soon as the water to be measured is in motion, or so soon as the science of hydraulics has been entered upon, we must get clearly in our minds the idea of rates of flow, or of a procession of such cubic volumes passing a given point in a certain unit of time, as of a flow of so many cubic feet per second.

Very little can be added to what Mr. Herschel has here said. It is a clear exposition of the whole subject. Such units as cubic feet per day and cubic miles have clearly no place in a modern paper on hydrology.

The unit of inches on the catchment area may, however, be pointed out as an exception to the foregoing general rule. This unit is exceedingly convenient because it admits of expressing rainfall and run-off in the same unit and without reference to the area. It brings out a number of relations not otherwise easily shown, as will be exhibited in discussing the tables accompanying this paper.

MINIMUM FLOW OF STREAMS.

Very little can be added to our knowledge of the minimum flow of streams beyond what has already been stated in *Water Supply and Irrigation Paper No. 24, Water Resources of the State of New York, Part I*, which applies particularly to streams in the State of New York. Summarizing the information there given, we may say that for streams issuing from regions of heavy, compact soil, mostly deforested, the extreme minimums are likely to run as low as 0.1 of a cubic foot per square mile per second. They may even in an extreme drought go as low as 0.05 of a cubic foot per square mile per second.

^a *Measuring Water*, by Clemens Herschel; An address to the students of Rensselaer Polytechnic Institute, Troy, N. Y.

Oswego River, by reason of large lake pondage, has a minimum flow of about 0.3 of a cubic foot per square mile per second. For a similar reason the Upper Hudson will not usually go less than 0.3 of a cubic foot per square mile per second, although in the summer of 1899 it probably did not exceed 0.2 of a cubic foot per square mile per second. This, however, was unusual. The streams of Long Island, issuing from sand plains, may be expected to give minimum flows of from 0.5 to 0.6 of a cubic foot per square mile per second. The streams of the northern part of New York, issuing from denser forests than the others, also give minimum yields somewhat in excess of 0.3 of a cubic foot per square mile per second. The streams tributary to Mohawk River, on the south side of the valley, will give minimum flows of not more than one-half of what the streams tributary on the north side give. As to the streams of the far West, many of them are frequently dry for several months at a time. A typical stream of this character is the Platte River, with a catchment area at Columbus, Nebr., of 56,867 square miles.^a

CHARACTERISTICS OF THE MINIMUM RUN-OFF.

Since the rainfall varies so widely, the run-off, which is a function of the rainfall, will also vary widely. On the Hudson River the maximum run-off of 33.08 inches, with a rainfall of 53.87 inches, occurred in 1892. The minimum, with a run-off of 17.46 inches and a rainfall of 36.37 inches, occurred in 1895. On the Genesee River the observed maximum rainfall of 47.79 inches, with a run-off of 19.38 inches, occurred in 1894.^b The minimum rainfall of 31 inches, with a minimum run-off of 6.67 inches, occurred in 1895. These figures of rainfall indicate that either the extreme maximum or the extreme minimum rainfall has not yet occurred on the catchment area of this stream.

On the Muskingum River the maximum rainfall thus far observed is 56.97 inches, with a maximum run-off of 26.84 inches, which occurred in 1890. The observed minimum rainfall of 29.84 inches, with the corresponding minimum run-off of 4.9 inches, occurred in 1895. It is also doubtful if either the extreme maximum or the extreme minimum rainfall has been yet observed on the catchment area of this stream. As to whether the rainfall will go lower there is no certain way of determining. Moreover, 4.9 inches seems a very low run-off—and the run-off is not likely to be less than this figure. However, the run-off in any year depends very largely on the rainfall of the months from

^aFor an extensive list of streams of which the maximum and minimum flows are given, the following may be consulted:

- (1) Water Power of the United States, Tenth Census, Vol. I, pp. XXVIII and XXIX.
- (2) Twentieth Ann. Rept. U. S. Geol. Survey, Part IV, Hydrography, pp. 46-63.
- (3) Report on water supply, water power, the flow of streams and attendant phenomena, by Cornelius C. Vermeule: Final Report State Geologist of New Jersey, Vol. III.

^bIn the combined Genesee River and Oatka Creek record the maximum run-off of 21.22 inches occurred in 1890, when the rainfall is placed at 47.54 inches. This, however, is less reliable than the rainfall and run-off of 1894, which latter is accordingly given the preference.

December to May, inclusive. There may possibly be, therefore, a lower annual run-off than 4.9 inches, even though the total rainfall should exceed 29.84 inches. The rainfall for December to May, inclusive, was 13.04 inches. The run-off for that period was 4.04 inches.

DIVISION OF STREAMS INTO CLASSES.

The foregoing statements indicate that, as regards run-off, streams of the eastern part of the United States may be divided into classes. In the first class will fall streams where the maximum rainfall is from 50 to 60 inches, with corresponding run-off somewhat more than one-half of the rainfall. The minimum run-off will be about one-half the rainfall, or a little less. These statements, it may be again repeated, are general ones, to which there are exceptions.

Another class of streams, of which the Genesee and Muskingum rivers are typical, are those with maximum rainfall on their catchments of 40 to 50 inches and with corresponding run-off somewhat less than one-half the rainfall. The minimum run-off for these streams is from one-fourth to one-sixth of the corresponding rainfall, or from about 16 per cent to 25 per cent.

A further class, the far Western streams, may be mentioned, in which the run-off is only a very small percentage of the rainfall, in some cases not more than $\frac{1}{4}$ per cent to 5 per cent, or at times even less. Probably comprehensive study would further subdivide these streams, but the intention at present is to merely call attention to some of the more marked peculiarities as a basis for final detailed study.

If one takes the streams of the far West, as, for instance, Loup River, in Nebraska, with a catchment area of 13,542 square miles, where the rainfall in 1894, observed at 24 stations, was, on an average, only 12.84 inches and the run-off of the stream did not much exceed 1 inch, he will find entirely different conditions from those above stated. In many cases streams in that locality run much less than 1 inch. For instance, the South Platte, at Denver, Colo., in 1896, with a rainfall of 11.84 inches, ran 0.62 inch. The catchment area at this place is 3,840 square miles. At Orchard, Colo., the South Platte, in 1898, with a rainfall of about 17 inches, ran 0.9 inch. The catchment area at this place is 12,260 square miles. The Republican River, at Junction, Nebr., with a rainfall of about 26 to 28 inches, in 1898, ran 0.39 inch. The catchment here is 25,837 square miles in extent.

The foregoing statements indicate the essential truth of the proposition already announced that, broadly, each stream is a law unto itself. Any formula, for either maximum, average, or mean run-off, which does not take this into account is incomplete.

ESTIMATION OF RUN-OFF FROM RAINFALL DIAGRAMS.

Can run-off of streams be estimated from diagrams of monthly rainfall? The writer has spent considerable time on this problem without

arriving at any very satisfactory conclusion. For some months such a diagram may be made to fit quite closely, while for others differences of as much as 2 or 3 inches appear. The conclusion of the writer is, therefore, that such diagrams are at the best crude approximations. Such study is, however, very fascinating, and it is not surprising that different hydrologists have attempted at various times its solution. Two lines of work may be mentioned. One is, by a combination of a large number of streams and their rainfall, to attempt to produce a universal formula. This, however, as has been already shown, leads to what is, in effect, a hodgepodge. Averages so applied "bring out class likenesses, to the exclusion of individual features."

The other method is to plat rainfall and run-off appearing monthly in inches, as abscissas and ordinates, respectively, and in this way to preserve the individual peculiarities of each stream. In some respects the most satisfactory way is to plat the rainfall and run-off of the storage, growing, and replenishing periods, thus grouping similar characteristics.

STORAGE IN LAKES.

The run-off of a stream is very materially influenced by the number of lakes within its catchment area. If there are many, flood flows may be expected to be very much smaller than they otherwise would be. The temporary pondage in the lakes is the cause of this. The Oswego River is a stream of this character. This stream has a total catchment area of 5,002 square miles, with something like 530 square miles of area of water surfaces—lakes, flats, and marshes. It appears, therefore, that the total area of water surfaces, flats, and marshes is about 10.6 per cent of the whole. The following lakes, ponds, and marshes are included in this catchment area: Canandaigua, Keuka, Seneca, Cayuga, Owasco, Skaneateles, Otisco, Cross, Onandaga, Cazenovia, Oneida, and Montezuma Marsh, together with a considerable number of miscellaneous small ponds and broad flat valleys.

To illustrate how these great natural reservoirs tend to prevent floods it may be mentioned that the configuration of Cayuga outlet, with relation to Clyde River, is such that frequently when there are heavy rainfalls in the catchment area of Clyde River the entire flood flow of Clyde River is discharged into Cayuga Lake, without affecting Seneca River below the mouth of Clyde River at all. It is undoubtedly due to this fact that fall floods on Oswego River are almost entirely unknown.

The evaporation of Oswego River catchment area is exceedingly large—about 28 inches—whence it results that the run-off from a mean annual rainfall of from 36 to 37 inches does not exceed about 9 or 10 inches. Owing to the large lake pondage the flood flows of this stream do not often exceed about 6 cubic feet per square mile per second.^a

^aSee report to the United States Board of Engineers on Deep Waterways for extended discussion on Oswego River.

COMPUTATION OF ANNUAL RUN-OFF.

No general rule can be formulated for computing annual run-off. The formulas of Mr. Vermeule are excellent formulas of the purely empirical class, applying fairly well to many streams in the northeastern part of the United States, but they do not apply at all to streams of the Middle West and Far West. Nor do they apply to some streams in the northeastern section. Nevertheless, they take into account the ground water, and are the most useful formulas thus far devised. It may be mentioned that Mr. Vermeule especially disclaims any intention of working out any formulas applying outside of the State of New Jersey. His general formula is in the nature of a suggestion.

DISCREPANCIES IN COMPUTATION OF RUN-OFF.

In computing the run-off of various streams small discrepancies will continually appear, and when such do not exceed 1 to 2 inches they are outside the limit of discussion. The question does not admit of such minuteness as to permit the discussion of small differences, although a difference of 2 inches on several thousand square miles would be much more serious than on the usual municipal catchment area of from 20 to 100 square miles. The size of the catchment area should, therefore, in this particular be taken into account.

Moreover, the run-off of streams has thus far been almost universally overestimated. Only a few are really down to the actual fact. Probably in no department of professional work are there more things to be taken into account than here.

ACTUAL GAGINGS PREFERABLE TO GENERAL STUDIES.

While on the general subject of the computation of run-off the writer may repeat what he has said in his report to the United States Board of Engineers on Deep Waterways, viz:

The data for estimating the water supply of a large canal, especially when on a large scale, should be based, when such data are available, upon actual gagings of streams, rather than on general considerations derived from study of the rainfall alone. An examination of a large number of estimates of canal water supplies, based on the usual method, shows that rainfall data alone are in close cases inadequate for solving a water-supply problem of the magnitude of the one now under consideration. When, however, actual gagings of the streams, extending over a sufficient number of years, are available, there is no reason why a water-supply problem on a large scale may not be worked out with the precision of a proposition in mathematics.

What is here said in regard to water supplies for canals is equally true as regards all other water supplies, either municipal or for water power, etc. Further on in the same chapter it is stated:

It is not intended to say, however, that rainfall data are not of use in a hydrologic discussion. When, as in the present case, in addition to stream gagings an

extended series of such data are available, the argument is made doubly good and the demonstration strengthened.

When records of gatings are available the computation becomes very simple. It is merely a matter of simple addition and subtraction.

The complete data required in order to compute the safe possible yield of a stream are as follows:

1. The catchment area.
2. The rainfall of the minimum year, as well as for a series of years.
3. A ground-water diagram of the stream or, lacking such, a diagram for a neighboring stream lying in the same or a similar geologic formation, and, so far as possible, with similar conditions of forestation.
4. The available storage capacity of the stream.
5. The loss by water surface evaporation from the reservoirs, together with an estimate of the loss by percolation.

The data required for ordinary computations may be frequently limited to the totals of the storage, growing, and replenishing periods, although when ground water is to be taken into account the monthly data should be given. The accompanying tables, Nos. 1 to 12, inclusive (pages 85-98), illustrate how such information may be placed in form for convenient use.

FORMULAS FOR RUN-OFF.

At the risk of being considered somewhat elementary the writer will give the more important of the formulas for run-off, expressed in terms of inches on the catchment area.

$$I_m = \frac{n \times Q \times 86400 \times 12}{A \times 640 \times 43560} \quad (5)$$

Whence we deduce,

$$I_m = \frac{n \times Q \times C_1}{A} \quad (6)$$

Also,

$$I_y = \frac{Q \times C_2}{A} \quad (7)$$

and

$$D = \frac{Q}{A} \quad (8)$$

To change gallons per day into inches per month we have:

$$I_m = n \times G \times C_3 \quad (9)$$

Also,

$$G = \frac{I_m}{n \times C_3} \quad (10)$$

In the reports of the United States Geological Survey, the discharge of streams is sometimes given in acre-feet per month. To reduce such to inches per month, we have, when total acre-feet are given,

$$I_m = \frac{B \times C_4}{A} \quad (11)$$

In these formulas,

A=area of catchment in square miles.

B=total acre-feet per month.

D=cubic feet per second per square mile.

G=gallons per day.

I_m =inches in depth per month on the catchment area.

I_y =inches in depth per year on the catchment area.

n =number of days per month.

Q=cubic feet per second flowing from the catchment area, as determined by gagings.

$$C_1 = \text{constant} = \left(\frac{86400 \times 12}{640 \times 43560} \right).$$

$$C_2 = \text{constant} = \left(\frac{86400 \times 12 \times 365}{640 \times 43560} \right).$$

$$C_3 = \text{constant} = \left(\frac{12}{7.48 \times 640 \times 43560} \right).$$

$$C_4 = \text{constant} = \left(\frac{12}{640} \right).$$

The constants, C_1 , C_2 , C_3 , and C_4 , are left in form for logarithmic computation. For a given case, catchment area is constant, and A, in the final logarithmic form, will be combined with these.

MAXIMUM DISCHARGE FORMULA.

A considerable number of such formulas have been worked out, but the authors have taken into account so few of the controlling conditions, that they are, at the best, mostly only crude guides, and the writer long ago gave up their use, except in cases where only the roughest approximation was required. Two exceptions may, however, from the peculiar form of the coefficient, be briefly noted, viz:

$$\text{Dickens's formula, } D = C\sqrt{M^3}; \text{ and} \quad (12)$$

$$\text{Ryves's formula, } D = C\sqrt{M^2}. \quad (13)$$

In these formulas, D=discharge in cubic feet per second; C=a coefficient, depending for its value upon rainfall, soil, topographical slope, elevation, size of the stream, shape of the catchment, etc., and M=area of the catchment in square miles.

COEFFICIENT TABLE FOR REPRESENTATIVE AREAS.

In Mullins's Irrigation Manual^a there are given tables for the value of the coefficients of these two formulas, together with the correspond-

^aIrrigation Manual, by Lieut. Gen. J. Mullins (published for Madras Government), 1890.

ing depth in inches, drained off from the given areas, and the discharges in cubic feet per second. These two formulas are cited because they take into account the principle of the sliding coefficient, as does the Kutter formula, a principle which, all things considered, is the most useful thus far devised. It is true that maximum discharge formulas have been devised taking into account average slope, depth, and intensity of rainfall, area of the mountainous part of the watershed and area of flat part of the same in square miles, and length of stream from source to point of discharge. These formulas, however, also involve from one to two coefficients and become complicated in use without, it is believed, any special gain over the simpler expressions cited. The formulas of Dickens and Ryves, which comprise within the coefficient C everything included in the more complicated formulas, were the forerunners of all formulas of this class.

COOLEY'S FORMULAS.

In an able paper^a Mr. George W. Cooley, C. E., gives the following formulas for run-off:

For a watershed without lakes,

$$F=0.844 LRC. \quad (14)$$

For a watershed with large lakes as receiving reservoirs,

$$F=(R+\frac{LRC}{W}-E)\times 0.844 W. \quad (15)$$

In which, F=flow in cubic feet per second.

R=precipitation in feet.

L=land surface of watershed in square miles.

W=Water surface of reservoirs in square miles.

E=Evaporation in feet.

C=Coefficient of available rainfall.

The constant 0.844 is equal to the number of feet in a square mile divided by the seconds in a year.

In these formulas the sliding coefficient is also recognized. The results, however, are based on averages, although it seems clear enough that in either power or water supply works what is wanted is the minimum run-off for a year or a series of years. For instance, the minimum rainfall at Lake Minnetonka in 1889 was only 18.36 inches, while the maximum in 1892 was 37.90 inches, or a little more than double the minimum. It is evident enough to any person who has gaged streams extensively that the run-off in 1889 must have been very much less than in 1892. In the absence of statements as to the amount of run-off in 1889, the writer can only estimate it, but

^aHydrology of the Lake Minnetonka watershed, by George W. Cooley, C. E.: Monthly Weather Review, January, 1899.

he doubts if it were over 10 per cent to 12 per cent of the rainfall. Probably about 2 inches is not far from the mark. What is wanted, therefore, is a concise statement, not only in this case but in every other, of the run-off of the year or series of years of minimum rainfall.

DANGER OF USING AVERAGES.

The writer has dwelt upon the foregoing point somewhat because only a very few of the more advanced students of hydrology have thus far fully appreciated its importance. A very large proportion of all the papers and reports prepared in the last ten years have proceeded on the supposition that safe deductions could be made from an average run-off. It is needless to say that all such are, without exception, erroneous. What is wanted is a clear statement of the minimum, together with the longest period which such minimum may be expected to occupy. A study of the meteorological records of the State of New York shows that the minimum period may be expected frequently to extend over three years. In the writer's report to the United States Board of Engineers on Deep Waterways, in the chapter on the meteorology of New York and the relation of precipitation to run-off, a large number of specific cases are cited, but space will not be taken here to discuss them. This proposition is true for other regions than the State of New York.

DANGER OF USING PERCENTAGES.

A much greater danger arises from the use of percentage of rainfall appearing in run-off. In many reports and papers it is assumed that averages of a series of percentages can be safely taken. The following illustration, with five cases drawn from observation, may be taken to show that this is erroneous:

Run-off, per cent of rainfall.

Case.	Rainfall.	Run-off.	Per cent.
	<i>Inches.</i>	<i>Inches.</i>	
1.	44.3	20.1	45.37
2.	62.5	35	56
3.	16.2	1.2	7.41
4.	24.3	2.5	10.29
5.	40.4	13.1	32.42
	187.7	71.9	5)151.49

$$\frac{\text{Run-off}}{\text{Rainfall}} = \frac{71.9}{187.7} = 38.31$$

$$\text{Difference} = 8.02$$

As a corollary to the preceding proposition, it follows that the ratio between annual rainfall and run-off known as the "run-off coefficient or factor" is essentially misleading. A realization of this fact has led the writer, in his report to the United States Board of Engineers on Deep Waterways, to practically expurgate this statement, or anything approximating to it, from his report. The expressions "average run-off" and "percentage of the rainfall" do not appear.

Attention may also be again directed to the fact that the total run-off of a stream in any given year depends very largely on the run-off of what may be termed the "storage period." Usually about 0.75 to 0.85 of the total rainfall of this period appears as run-off in the stream, while for the summer, or growing period, not more than about 0.1 of the rainfall appears. This great difference is due to greater evaporation, as well as to the absorption of water by plants during this period. The total amount for the year which will appear as run-off in the stream will depend, therefore, very largely on whether or not the rainfall of the storage period—December to May, inclusive—is large or small. If the winter rainfall is relatively large, the run-off will also be relatively large, even though the total rainfall for the year is small. This fact must be taken into account in estimating the value of streams. Whether any given stream is low during the summer months or has then a well-sustained flow will depend very largely on the rainfall of the month of May. When the May rainfall is heavy enough to produce full ground water, the flow is likely to be well sustained, even though the rainfall is comparatively low during the summer months following. If, on the contrary, the May rainfall is so low as to leave a deficiency in ground water for that month, the flow will be low during the summer, even though the rainfall is large.

The foregoing also explains why for certain years the run-off of a stream may be relatively small, even with rainfall considerably above the average.

To more particularly illustrate this, assume a stream with, say, 6 inches of ground-water flow and further assume that on any convenient date the ground water is practically depleted. Under these circumstances, the 6 inches of ground water must fill up before any very large flow can occur. On the other hand, we may consider the sequence of the rainfall such as to leave full ground water, whence it results that there will be a much larger run-off, even though rainfall and other conditions are the same.

What is wanted in a stream, therefore, is as large a ground flow as possible, with small evaporation. That there are very great differences in streams in this respect may be easily seen by examining a series of tables of stream flow. It may be remarked that these two conditions are obtained only on a forested area, for proof of which see Bulletin No. 7, Department of Agriculture, Forest Influences.

EFFECT OF LOW GROUND WATER.

Moreover, when rainfall is below the mean for several months, the ground water may be expected to become continuously lower. This is a subject about which comparatively little is known, although the data are very important in estimating the permanency of a stream. Aside from Mr. Vermeule's, the most satisfactory discussion which the writer has seen is that of Mr. W. S. Auchincloss.^a This paper, while too long to be abstracted, is nevertheless very interesting, because the author recognizes the limitations of averages. On page 10, after giving a table of the average rise of his sublake, he states:

Since the table was built up from averages, we must not expect it to emphasize special variations, for the grouping of averages resembles the grouping of pictures in composite photography. The combination invariably brings out class likenesses to the exclusion of individual features. Thus the table loses sight of an extraordinary year like 1889—full of plus quantities—also seasons of drought, like 1894 and 1895. It, however, clearly shows that influx has a tendency to prevail between February and July, inclusive, and efflux to hold the mastery during the remaining months of the year.

Though this paper does not fully recognize the wide variation occurring at different localities, this is probably not due to oversight, but merely to the fact that the author was discussing a specific case. The observations recorded were made at Bryn Mawr, Pa. The paper is valuable and well worth the attention of students of hydrology.

VERMEULE'S FORMULAS.

These formulas are somewhat different from those previously considered. Mr. Vermeule claims to have discovered a relation between evaporation and mean annual temperature. For the relation between annual evaporation and annual precipitation on Sudbury, Croton, and Passaic rivers he gives the following:

$$E=15.50+0.16 R, \quad (16)$$

In which E=the annual evaporation and R=the annual rainfall.

In the original publication of his formula, in the Report of the Geological Survey of New Jersey,^b Mr. Vermeule allowed for other catchment areas an increase or decrease of 5 per cent from values given for evaporation on the Sudbury, Croton, and Passaic rivers. The following is his general formula for all streams:

$$E=(15.50+0.16 R) (0.05 T-1.48) \quad (17)$$

This, however, he states is merely a suggestion. His purpose is to deduce laws which hold for the State of New Jersey alone.

In these formulas the evaporation is taken to include all the various losses of water to which a catchment area is subject, including direct evaporation as well as water absorbed and transpired by plant growth, etc. Hence,

$$F (\text{run-off})=R-E. \quad (18)$$

^a On Waters within the Earth and Laws of Rainflow, by W. S. Auchincloss, C. E. Philadelphia, 1897.

^b Report on water supply, water power, the flow of streams, and attendant phenomena, by C. C. Vermeule: Final Report State Geologist of New Jersey, Vol. III. Trenton, 1894.

Mr. Vermeule gives the following formulas for the Sudbury, Croton, and Passaic rivers:

$$\text{December-May, } E=4.20+0.12 R; \tag{19}$$

$$\text{June-November, } E=11.30+0.20 R. \tag{20}$$

These formulas take into account the fact that evaporation is low in the winter months and high during the summer.

Mr. Vermeule also gives the following formula for computing monthly evaporation from the monthly rainfall for Sudbury, Croton, and Passaic catchment areas:

[e=monthly evaporation; r=monthly rainfall.]

December	e = 0.42+0.10 r	}	
January	e = 0.27+0.10 r		
February	e = 0.30+0.10 r		
March	e = 0.48+0.10 r		
April	e = 0.87+0.10 r		
May	e = 1.87+0.20 r		
June	e = 2.50+0.25 r		
July	e = 3.00+0.30 r		
August	e = 2.62+0.25 r		
September	e = 1.63+0.20 r		
October	e = 0.88+0.12 r		
November	e = 0.66+0.10 r		
Year	e = 15.50+0.16 r		

To obtain the monthly evaporation for other streams the results obtained are multiplied by the following:

$$(0.05 T - 1.48.)$$

In which T=mean annual temperature.

At this point Mr. Vermeule was confronted by the difficulty of ground storage. In regard to the effect of this it may be mentioned that, with rainfall above the average continuously for several years, ground water may be expected to stand above its average height, yielding to streams the maximum flow possible to ground water. On the other hand, when the rainfall is below the average for a number of years ground-water flow will be lower, becoming less and less as the rainfall approaches the minimum. It is very important that this fact be taken into account, because without it one is certain to fall into error. The formulas for average depletion may be given as follows:

$$d_2 = d_1 + e + f - r; \tag{22}$$

$$d = \frac{f}{2} + d_1 - \frac{r - e}{2}. \tag{23}$$

In which d_1 and d_2 =depletion at end of previous month and for the month under consideration; d =average depletion; e and r =monthly evaporation and monthly rainfall, respectively, and f =computed monthly flow.

The foregoing does not fully express the use of these formulas, but as all that is wanted at this time is an illustration of methods, this brief account may be deemed sufficient.

Mr. Vermeule gives a diagram showing ground flow for the several different streams mentioned for a given depletion, which is to be used in conjunction with the foregoing formulas. In his opinion the diagrams present advantages over a ground-flow formula with varying constants and coefficients for different streams, being more readily compared and insuring greater accuracy. Later, in his report on forests,^a Mr. Vermeule modifies his formula, as follows:

$$E = (11 + 0.29 R) M. \quad (24)$$

In which E=evaporation, R=rainfall, and M is a factor depending upon the mean temperature of the atmosphere. The writer understands Mr. Vermeule to say that this is also an expression for annual evaporation.

Values of M for given mean annual temperatures are as follows:

40°, 0.77; 41°, 0.79; 42°, 0.82; 43°, 0.85; 44°, 0.88; 45°, 0.91; 46°, 0.94; 47°, 0.97; 48°, 1; 49°, 1.03; 50°, 1.07; 51°, 1.10; 52°, 1.14; 53°, 1.18; 54°, 1.22; 55°, 1.26; 56°, 1.30; 57°, 1.34; 58°, 1.39; 59°, 1.43; 60°, 1.47; 61°, 1.51.

In a table on page 149 of the Report on Forests Mr. Vermeule compares observed annual evaporation with computed annual evaporation. The following are some of the differences which appear:

On the Genesee River the observed annual evaporation is 27.2 inches; computed annual evaporation, 20.6 inches; the observed annual evaporation, therefore, is 6.6 inches, or 32 per cent, greater than the estimated annual evaporation. On the Musconetcong River the observed, as compared with the computed evaporation, is 13 per cent less; on the Pequest it is 17 per cent less; on the Paulinskill it is 14 per cent less; on the Tohickon, 32 per cent less; on the Neshaminy, 16 per cent less; on the Perkiomen, 17 per cent less; on the Desplaines, 21 per cent greater; on the Kansas, 15 per cent greater; on the Upper Hudson, 10 per cent greater; on Hemlock Lake, 18 per cent less; on the Potomac, 17 per cent less; on the Savannah, 13 per cent less. For the rest of the streams cited in the table the agreement is closer than this.

The observed annual evaporation is 32 per cent greater than the computed annual evaporation on the Genesee River and 32 per cent less on Tohickon Creek—a range of 64 per cent. Somewhat similar differences are found on other streams where the gagings are approximately right. As to the gagings referred to in the report on forests, the writer will show farther on in this paper that gagings of Genesee and Hudson rivers are, on the whole, probably the best thus far made in the United States. Tohickon, Neshaminy, and Perkiomen creeks have been gaged by Francis weirs, and are, with the exception of Tohickon, considered approximately right. The difficulty here is probably in the flood flows. The writer understands

^a Report on forests, by C. C. Vermeule: Ann. Rept. State Geologist New Jersey for year 1899, Trenton, 1900.

that Mr. Vermeule used the Francis formula for a sharp-crested weir. The gagings of Sudbury, Cochituate, and Mystic rivers have been deduced, it is believed, by Mr. Francis's formula for the Merrimac dam. As to Desplaines River, a discharge curve determined by current meter has, it is believed, been applied.^a The English streams cited, Lea, Wandle, Thames, etc., have probably been gaged by a sharp-crested weir, and the others mostly by the current meter and a rating table.

RUSSELL'S FORMULAS.

Mr. Thomas Russell^b gives the following formulas for the run-off of the Ohio, Upper Mississippi, and Upper and Middle Missouri valleys, in terms of the annual rainfall. For the Ohio River the formula is as follows:

$$O = 0.600 + 0.95 R - 0.90 R (0.975 e - 0.421 e^2 + 0.626 e^3). \quad (25)$$

For the Upper Mississippi it is:

$$O = 0.50 + 0.93 R - 0.88 R (1.131 e - 0.383 e^2). \quad (26)$$

For the Upper and Middle Missouri it is:

$$O = 0.12 + 0.98 R - 0.93 R (0.91 e - 0.220 e^2 + 0.009 e^3). \quad (27)$$

In these formulas R is the rainfall for the month in cubic miles; e is the quantity of water required to saturate the air at any time, equal to the difference between what the air contains and the amount if it was saturated; and O is the outflow or run-off.

These formulas are interesting in the present connection, because they recognize the fact that every stream must have its own formula. The variation in run-off on the Ohio, Mississippi, and Missouri rivers will be observed on inspection of the formulas. Like all formulas of this class they are subject to considerable variation. In the month of October, 1881, the computed outflow of Missouri River was 4.9 cubic miles and the observed flow was 1.6 cubic miles, a difference of 3.3 cubic miles.

RELATION BETWEEN CATCHMENT AREA AND MAXIMUM, MINIMUM, AND MEAN RUN-OFF.

It is quite common for hydrologists to assume that there is a relation between catchment area and maximum, minimum, and mean run-off, the general proposition being that mean annual run-off varies inversely as the size of the catchment, and that maximum run-off, or flood flow, varies directly as the size of the catchment.

In order to gain some idea as to the applicability of this proposition, the résumé of discharge data, in the Twentieth Annual Report of the

^aData pertaining to rainfall and stream flow, by Thomas T. Johnston: Jour. Western Soc. Engrs., Vol. I, No. 3, June, 1896.

^bRainfall and river outflow in the Mississippi Valley, by Thomas Russell: Ann. Rept. Chief Signal Officer for the year 1889, Part I, Appendix 14.

United States Geological Survey, pages 46-64, has been examined. This table includes about 225 streams in various portions of the United States, with records ranging from 18 to 20 years in length to 1 year. A few of the best-known streams—as, for instance, the Croton and Sudbury—are not given in detail, although the large number included in this table, it is believed, is sufficient to settle definitely this question. Only a very few of the results will be referred to here.

In the first place, it appears certain that with equal rainfall there is no very definite relation between size of catchment area and mean annual run-off. For instance, the Kennebec, at Waterville, Me., with a catchment area of 4,410 square miles, has a mean annual run-off for 6 years of 22.4 inches. The Cobbosseecontee, at Gardiner, Me., with a catchment area of 230 square miles, has a mean annual run-off for 6 years of 18.5 inches. The Androscoggin, at Rumford Falls, Me., with a catchment area of 2,220 square miles, has for 6 years a mean annual run-off of 24.2 inches. The Presumpscot, at Sebago Lake, Me, with a catchment of 470 square miles, has a mean annual run-off for 11 years of 21 inches. The Merrimac, at Lawrence, Mass., with a catchment area of 4,553 square miles, has a mean annual run-off for 9 years of 21.3 inches. Aside from the Androscoggin River these five streams support the proposition that the run-off varies in some degree directly as the drainage area instead of inversely.

As to the maximum run-off, or flood flow, there is apparently some slight relation, although even this is less definite than has usually been assumed.

As to minimum run-off, there is apparently no relation, extremely small flows happening on large streams as well as on the smallest. There is, however, much more definitely a relation between the run-off and the rainfall, run-off increasing as rainfall increases, and conversely.

As regards the division of streams into classes in proportion to size of catchment area, it appears, therefore, that aside from maximum run-off one is not, on present information, justified in such classification, and even in cases of flood flow it is quite probable that there are other considerations of such importance as to render a classification of this character inexpedient.

In the rivers for which data are given in this paper the catchment areas vary from 18.9 square miles for Lake Cochituate to 10,234 square miles for the Connecticut River. Since there is no very definite relation between size of catchment and run-off there is no reason why the comparison may not be made of streams having such large difference in size of catchment. For some streams—as, for instance, Pequannock River—where the slopes are very steep, the run-off is somewhat higher than it would be with other conditions the same, but with flatter slopes. But generally the degree of forestation and other elements exercise so much more important an influence that a comparison, without regard to size of catchment area, may be legitimately

made. Nevertheless, this proposition is possibly debatable, and for the present the conclusions drawn are tentative merely.

THE EXTREME LOW-WATER PERIOD.

In the discussion of Tables Nos. 1-12, inclusive, the writer has given the low water of the minimum year, but this does not usually include the extreme low-water period, which is in almost every case much more than one year. Space will not be taken to show the extreme low-water periods of all these tables. It is considered that illustrations from Muskingum and Genesee rivers are sufficient. This information is given in Tables Nos. 14 and 15.

On the Muskingum River three low-water periods have occurred during the time covered by the gagings. The first was from December, 1887, to November, 1889, inclusive, a period of twenty-four months, during which the total run-off was 18.55 inches, or if we assume a reservoir on said stream of 20 square miles water surface, the total net run-off becomes 18.15 inches. The computations of evaporation, etc., for such a reservoir, neglecting variation in water surface, are as follows. Assume an annual evaporation of 40 inches and with distribution for the several months as per column 1 in the following table. Since the water surface area is 20 square miles, it becomes 20/5828 of the whole, or 1/292. Hence, water surface evaporation is 1/292 of 40 inches, and making the computation for each month, we have the quantities as per column 2:

Total evaporation and evaporation per square mile of water surface in Muskingum Basin.

Month.	1. Total evapora- tion.	2. Evapora- tion per square mile of water sur- face.
January	1.00	0.0034
February	1.10	.0037
March	1.70	.0058
April	3.00	.01029
May	4.60	.01578
June	5.65	.01938
July	6.10	.02092
August	5.60	.01921
September	4.15	.01423
October	3.35	.01149
November	2.25	.00772
December	1.50	.00514
	40.00	-----

With some allowance for percolation, leakage, etc., the total is taken at 0.40 of an inch per year. Analyzing the first period, we find that for 24 months there was an average flow of 0.76 inch per month, for 12 months an average flow of 0.67 inch, and for 9 months an average flow of 0.43 inch.

The second low-water period was from May, 1891, to January, 1893, inclusive, a period of 21 months, during which time the net run-off was 17.2 inches, yielding for the whole 21 months an average of 0.82 inch and for 7 months an average of 0.36 inch.

The most extreme low-water period was from April, 1894, to November, 1895, inclusive, a period of 20 months, during which time the net run-off did not exceed under the assumed conditions 7.09 inches. The average run-off for 20 months was 0.354 inch and for 7 months 0.116 inch.

On Genesee River there have been two low-water periods during the time covered by the gagings. The first was from June, 1894, to February, 1896, a period of 21 months, during which time there was a gross run-off of 13.02 inches. Evaporation has been computed for a proposed reservoir of 12.4 square miles water-surface area, with allowance for actual height of water during the different months. On this basis and with a small allowance for percolation, leakage, etc., the total evaporation loss for the 21 months becomes 0.65 inch, leaving a net run-off of 12.37 inches. The average run-off for 21 months was 0.59 inch, or, if we assume 1.43 inches left in reservoir at end of period, the average allowable run-off becomes 0.52 inch. For 10 months, with some allowance, the average run-off is 0.30 inch and for 7 months 0.10 inch.

The second period was from June, 1896, to December, 1897, a period of 19 months, during which time the net run-off was 13.24 inches. The average run-off for 19 months, with 1.24 inches left in reservoir at end of the period, was 0.63 inch; for 8 months, 0.31 inch, and for 6 months, 0.17 inch. These figures, without being exhaustive, show that Genesee River is a somewhat better water yielder than Muskingum River.

A large number of other interesting and valuable tabulations could be drawn from these data, especially those relating to storage. But since this element is not specially considered in this paper they are not given. In any case, enough has been said to sustain the statement that streams vary, not only as regards their total capability of yielding water, but as regards its distribution. In order to develop a stream to its maximum capacity for either water power or municipal purposes it is absolutely indispensable to have a series of carefully prepared gagings. Lacking these, there should be gathered as long a rainfall record as possible, from which, by comparison, the approximate run-off of the stream may be computed. A carefully taken series of gagings is, however, in every way preferable.

VARIATION IN WEIR MEASUREMENTS.

The writer has shown^a the considerable variation in weir measurements due to difference in form of weir alone. So great are these that any conclusions based upon the data of sharp-crested weirs applied to other forms are extremely unsatisfactory. In one case of a flat-crested weir, the flow at a given depth is only 75 per cent of what it is over a sharp-crested weir. Variations of from 5 per cent to 20 per cent are common, as may be easily observed by examining the tables in the paper cited.

In view of the importance which gagings are now shown to bear in estimating the value of a stream for water power or city water supply, in future every statement of stream flow should be accompanied by a concise statement of the method of gaging used, thus permitting hydrologists to judge of the general reliability of the method. Had this been done in the past, some of the uncertainty which now attaches to many gaging records would undoubtedly be removed.

GENESEE AND HUDSON GAGINGS REDUCED TO SHARP-CRESTED WEIR MEASUREMENTS.

The writer has shown in another place that Genesee River gagings which were made by him have been reduced to sharp-crested weir measurements. As to the Hudson gagings, Pl. CXXVII in the Report to the United States Board of Engineers on Deep Waterways may be cited. This plate is a comparison of the discharge over weirs by different formulas, and it appears from it that Mullins's formula for a flat-crested weir, which has been used for the Upper Hudson gagings, at a depth of 4 feet gives results less than Francis's formula for a sharp-crested weir by about 10 per cent. However, in order to simplify the computation and to avoid velocity of approach, the width of the crest was taken at 5 feet. Again, the crest at Mechanicville is not flat, but is slightly sloping backward. The sloping front probably affects the flow to increase it somewhat. There are also flashboards used during low water, which are properly computed by Francis's formula for a sharp-crested weir. These several elements undoubtedly make the problem somewhat complicated, but taking everything into account it is probable that the results as computed are not far from right. They may, however, be in error as much as 2 inches per year.^b

As regards the relation between mean annual temperature and evaporation, the questions raised by Mr. Vermeule are very interesting and have received considerable study from the writer ever since the publication of Mr. Vermeule's report in 1894. This study has been specially directed toward determining whether there was any

^aOn the flow of water over dams: Trans. Am. Soc. C. E., Vol. XLIV, p. 220.

^bSee the diagrams of Hudson and Genesee rivers on this point.

way of showing by diagrams, definitely, that any such relation really existed. A concise résumé of such study will now be given.

EVAPORATION.

FITZGERALD'S FORMULA FOR EVAPORATION.

In the first place we may consider Mr. FitzGerald's formula for evaporation,^a which is:

$$E = \frac{(V-v) \left(1 + \frac{W}{2}\right)}{60}. \quad (28)$$

In this formula V =the maximum force of vapor in inches of mercury corresponding to the temperature of the water; v =the force of vapor present in the air; W =the velocity of the wind in miles per hour; and E =the evaporation in inches of depth per hour. It can be shown that there is going on nearly always a condensation of moisture from the air upon any water surface. At the same time there is going on a loss of moisture from the water surface by evaporation. The intensity of both these operations depends upon the difference in temperature between the air and any water surface with which it may be in contact. When the temperature of air and water is the same, both processes stop. Evaporation is, therefore, in effect the measure of the difference of these two exchanges. The velocity of the wind is also seen to exert a very decided effect on the intensity of evaporation.

In the foregoing formula, v , the force of vapor present in the air is computed by the following:

$$v = V - \frac{0.480(t-t')}{689-t'}h, \quad (29)$$

In which v =the force of vapor in the air at the time of the observation;

t =the temperature of the air in centigrade degrees, indicated by the dry thermometer;

t' =the temperature of evaporation given by the wet thermometer;

V =the force of vapor in a saturated air at the temperature t' ; and

h =the height of the barometer.

There is no difference between evaporation from a water surface and evaporation from land, except that on a water surface it goes on continuously, while on land evaporation may be interrupted from lack of something to evaporate. The preceding formula shows that the force of vapor is dependent upon the difference of the dry and wet bulb thermometers, and not in any degree upon the mean annual temperature.

^aTrans. Am. Soc. C. E., Vol. XV, pp. 581-646.

EVAPORATION RELATIONS.

Prof. Cleveland Abbe^a gives the following relations of evaporation, as established by Prof. Thomas Tate:

(a) Other things being the same, the rate of evaporation is nearly proportional to the difference of the temperatures indicated by the wet-bulb and dry-bulb thermometers.

(b) Other things being the same, the augmentation of evaporation due to air in motion is nearly proportional to the velocity of the wind.

(c) Other things being the same, the evaporation is nearly inversely proportional to the pressure of the atmosphere.

(d) The rate of evaporation of moisture from damp, porous substances of the same material is proportional to the extent of the surface presented to the air, without regard to the relative thickness of the substances.

(e) The rate of evaporation from different substances mainly depends upon the roughness of, or inequalities on, their surfaces, the evaporation going on most rapidly from the roughest or most uneven surfaces; in fact, the best radiators are the best vaporizers of moisture.

(f) The evaporation from equal surfaces composed of the same material is the same, or very nearly the same, in a quiescent atmosphere, whatever may be the inclination of the surfaces; thus a horizontal plate with its damp face upward evaporates as much as one with its damp face downward.

(g) The rate of evaporation from a damp surface (namely, a horizontal surface facing upward) is very much affected by the elevation at which the surface is placed above the ground.

(h) The rate of evaporation is affected by the radiation of surrounding bodies.

(i) The diffusion of vapor from a damp surface through a variable column of air varies (approximately) in the inverse ratio of the depth of the column, the temperature being constant.

(j) The amount of vapor diffused varies directly as the tension of the vapor at a given temperature, and inversely as the depth of the column of air through which the vapor has to pass.

(k) The time in which a given volume of dry air becomes saturated with vapor, or saturated within a given percentage, is nearly independent of the temperature if the source of vapor is constant.

(l) The times in which different volumes of dry air become saturated with watery vapor, or saturated within a given per cent, are nearly proportional to the volumes.

(m) The vapor already formed diffuses itself in the atmosphere much more rapidly than it is formed from the surface of the water. (This assumes, of course, that there are no convection currents of air to affect the evaporation or the diffusion.)

EFFECT OF WIND AND OTHER METEOROLOGICAL ELEMENTS.

That the velocity of the wind must have a very material effect upon evaporation, and hence upon the run-off of streams, is at once apparent on inspection of Mr. FitzGerald's evaporation formula, given in a preceding chapter. Again, on examining the annual summaries in the report of the Chief of the Weather Bureau the average yearly velocity of wind is found to vary from about 3 miles to 16 or 18 miles.

^a Preparatory studies for deductive methods in storm and weather predictions, by Prof. Cleveland Abbe: Ann. Rept. Chief Signal Officer for 1889, Part I, Appendix 15.

With other conditions the same, evaporation will be much larger with a higher wind velocity.

The preceding summary of evaporation relations further shows that evaporation will vary in some degrees in proportion to pressure, temperature, moisture—which may be taken to include dew-point, relative humidity, vapor pressure, precipitation, and cloudiness—and, finally, in proportion to average velocity of the wind. It may also be expected to vary in some degree in proportion to electrical phenomena—thunderstorms, auroras, etc.—but as yet we know so little about these that they can be no more than mentioned. The writer, however, believes that studies in the direction here indicated would be very prolific of results. For this purpose two or three stations, observing all the elements herein enumerated, should be established in each catchment area.

In the present study an attempt has been made to correlate these elements with the run-off, but, aside from the rainfall, the data are too indefinite for satisfactory results. It is for these reasons, with others, that the writer is able to give only tentative conclusions in regard to the relation of rainfall to the run-off of streams.

PERSISTENCY OF RATE OF EVAPORATION.

The persistency of the amount of evaporation for any given stream at about the same figure through long periods of time was first pointed out by Messrs. Lawes, Gilbert, and Warrington in their classical paper, *On the Amount and Composition of Rain and Drainage Waters Collected at Rothampsted*, published in the *Journal of the Royal Agricultural Society of England* for 1881. As to why evaporation exhibits such persistency these distinguished authors consider it largely due to the fact that the two principal conditions which determine large evaporation—namely, excessive heat and abundant rain—very rarely occur together. The result is, especially in the English climate, a balance of conditions unfavorable to large evaporation. In a wet season, when the soil is kept well supplied with water, there is at the same time an atmosphere more or less saturated, with an absence of sunshine; while in dry seasons the scarcity of rain results in great dryness of the soil, with scant, slow evaporation.^a

NEGATIVE EVAPORATION.

In a strictly scientific sense this term is taken to mean that when the temperature of the evaporating surface is lower than the dew-point, water is deposited on that surface. As regards the rainfall, run-off, and evaporation tables, herewith included, negative evaporation means that the run-off for certain months is greater than the rainfall. Sometimes this may legitimately happen when a heavy rain-

^aSince the persistency of evaporation has been extensively discussed in the writer's paper on *Stream flow in relation to forests* (see footnote on p. 54), it is merely touched on here.

fall comes at the end of the month, or when, with much snowfall, the temperature of the month is mostly below freezing. In order to show as much as possible in regard thereto, the writer gives the detail for each of the 12 tables, together with a tentative view as to the real significance of the so-called negative evaporation.

On Muskingum River, during the 8 years gaged, negative evaporation is shown only twice for one month.

On Genesee River the detailed tabulation shows negative evaporation 5 times for one month and once for two consecutive months, a total of 7 months in all.

On Croton River, for the entire period of 32 years, negative evaporation is shown 29 times for one month and 6 times for two consecutive months, a total of 41 months in all.

On Lake Cochituate negative evaporation is shown 24 times for one month, 3 times for two consecutive months, and twice for three consecutive months, a total of 36 months in all. Negative evaporation is also shown once for the entire storage period in 1891.

On Sudbury River it is shown 16 times for one month, 9 times for two consecutive months, and 3 times for three consecutive months, a total of 43 months in all.

On Mystic Lake it is shown 12 times for one month, twice for two consecutive months, once for three consecutive months, and once for four consecutive months, a total of 23 months in all.

On Neshaminy Creek negative evaporation is shown 6 times for one month, 5 times for two consecutive months, and once for three consecutive months, a total of 19 months in all.

On Perkiomen Creek negative evaporation is shown 10 times for one month, twice for two consecutive months, and twice for three consecutive months, a total of 20 months.

On T'ohickon Creek it is shown 11 times for one month, 4 times for two consecutive months, twice for three consecutive months, and once for four consecutive months, a total of 29 months. The year 1884 shows a negative evaporation of 1.21 inches for the entire storage period, and the year 1899 a negative evaporation of 2.37 inches for the entire storage period. This latter is so large that it has seemed best to reject the year 1899. Probably the year 1884 should also have been rejected, but it has been allowed to remain.

On Hudson River negative evaporation is shown 7 times for one month and 4 times for two consecutive months, a total of 15 months.

On Pequannock River it is shown 9 times for one month and 5 times for two consecutive months, a total of 19 months.

On Connecticut River negative evaporation is shown 6 times for one month, 9 times for two consecutive months, and once for three consecutive months, a total of 27 months. The year 1873 shows -3.64 inches in the storage period, and for the year 1874 the positive evaporation of the storage period is only 0.04 inch; for 1876 it is for

the same period -2.24 inches. The years 1873, 1874, and 1876 have been rejected in computing the means.

The writer has no doubt that, except in cold climates, when negative evaporation occurs for three or more consecutive months, there is an error in the gagings. He also doubts their accuracy somewhat when negative evaporation appears for two consecutive months. As regards the storage period, there is no difficulty in accepting it for one month as true, because rainfall or snowfall at the end of the month can be easily carried over to the next. This is also true sometimes for two months, but for the present it seems quite doubtful that other than in exceedingly rare cases would negative evaporation occur for three consecutive months. Its occurrence for six consecutive months, or for the entire storage period, is believed to be impossible. It may, however, be again pointed out that its occurrence renders an attempt at monthly diagrams showing the relation between rainfall and run-off absurd.

Assuming that the foregoing propositions are reasonably true, it follows that the frequency of the occurrence of negative evaporation in gaging records may be in some degree a criterion as to their accuracy. The writer, however, does not wish to urge this very strongly, but merely to point it out as a possibility.

In reference to Tables Nos. 1-12, inclusive, it may be stated that these are really all that are available for such a discussion. There are several stream-flow records which are nearly as accurate as any herein included, but unfortunately they were not accompanied by records of rainfall, and the considerable labor of compiling and reducing these has prevented their use. There are also some records, with rainfall included, of which the gagings are not considered very reliable, and which, for the present, are left untouched on that account.

In a report on the flow of the river Thames, by A. R. Binnie, chief engineer of the London county council,^a the matter of negative evaporation is elaborately discussed, and in order to obtain all the information possible about it Mr. Binnie applied to George J. Symons, F. R. S., to assist him in arriving at some approximate idea on the subject. Mr. Symons submitted an exceedingly lucid and conclusive report. Eleven distinct cases of negative evaporation were submitted to him for study and comment. In regard to these he arrived at the following conclusions:

- (1) Under normal conditions a fall of rain will increase the flow at Teddington weir on the second day after it falls.
- (2) Under normal conditions the water running off from any given fall of rain will all reach Teddington weir before the tenth subsequent day.
- (3) In the winter an interval of two months, or in extreme cases even more, may elapse between the precipitation of moisture from the clouds and its flow over Teddington weir.

^aReport on the Flow of the River Thames, by A. R. Binnie. Publication of the London County Council, dated November 1, 1892.

As a consequence of (2) it is clear that a heavy rainfall on the last days of any month may not appear at the point of gaging until the next month. Mr. Symons also states that the one great fact which has been impressed upon him by these investigations is the great effect of winter frosts in regulating the flow of the river Thames and in mitigating winter floods.

These conclusions are more especially intended to apply to the river Thames. Hence, while it is true that so-called negative evaporation exists on all of the streams considered, the conditions are nevertheless very different, and in the United States the effect of holding back the flow of streams by frosts is in very many cases to precipitate a flood of water later on. This element would hardly be considered with us as either a river regulator or as mitigating floods.

GROUND WATER.

MOVEMENTS OF GROUND WATER.

In an extensive paper Prof. F. H. King has very clearly defined many of the underlying principles covering the movements of ground water.^a In the beginning of his paper Professor King remarks that there is no single substance entering into the structure of the earth which has played and is playing so important a part as water. It penetrates the soils, sands, and rocks of the land areas in such large quantities that sand and sandstones lying below water level may contain as high as 38 per cent of their volume of water. Even the quantity stored in soil, gravel, and clay is very large. The water in a saturated soil or clay may range from 22 per cent up to 40 and even 50 per cent of its dry weight. The following table, giving the water capacity of undisturbed soils when lying below the plane of saturation, shows the amount of water which may be contained in various soils under natural conditions:

Water capacity of undisturbed soils.

Kind of soil.	Depth of layer.	Per cent of water.	Inches of water.
	<i>Inches.</i>		
Marly loam	0 to 12	41.3	5.88
Reddish clay	12 to 24	28.1	5.03
Do	24 to 36	28.4	5.07
Clay with sand	36 to 48	24.8	4.67
Very fine sand	48 to 60	17.4	3.76
Total			24.41

^aPrinciples and conditions of the movements of ground water, by F. H. King: Nineteenth Ann. Rept. U. S. Geol. Survey, Part II.

Professor King states that there are many reasons for believing that water penetrates the fissures and interstices of the earth to depths even exceeding 10,000 feet. If the waters so inclosed form no larger part than 1 per cent of the weight of the material, with a specific gravity of 2.65, the amount of inclosed water would be sufficient to form an envelope 265 feet deep.

Moreover, Professor King's observations show that ground water is very easily disturbed and is constantly in motion. It responds readily to changes in barometer, temperature, etc. It is evident that these movements are not only closely related to the rainfall, the source of ground water, but that the run-off of streams is considerably influenced thereby.

GROWTH OF STREAMS BY ACCESSION OF GROUND WATER.

It is evident, without special discussion, that streams winding through the thread of a valley must receive accession to their volumes little by little as they move along. A few such, cited by Professor King, may be mentioned.

1. The Los Angeles River, in California, was measured in the winter of 1897-98, showing that in a distance of 59,088 feet (11.19 miles) the river increased in volume from 20.41 cubic feet per second to about 80 cubic feet per second. The width of the river will average perhaps 40 feet, and adding to this 5 feet on each bank, through which water may enter the stream, we have a seepage surface of 50 square feet per linear foot of length, whence we have a total seepage surface of 2,954,400 square feet. We have then for this particular case an average rate of seepage of 0.0000203 of a cubic foot per square foot per second.

This computation is made without reference to gradient, which is unknown.

A profile of the growth of the Los Angeles River is also given, which shows that the rate of accession is not uniform, but that much the larger portion of it takes place in the upper 47 per cent of the total length.

2. The West Los Angeles Water Company has a flume about 4,500 feet long sunk below the normal level of the ground water for the purpose of collecting the same and delivering it at the surface lower down the valley. The flume is described as being rectangular in cross section, 4 feet deep and 5 feet wide, with open bottom, but covered and provided with wooden sides.

On January 21, 1897, the flume was discharging 7.2 cubic feet per second; on November 19, 1896, 7.29 cubic feet per second; on March 1, 1896, 8.5 cubic feet per second; on November 23, 1895, it is said to have discharged 10.1 cubic feet per second, but in April, 1898, it was discharging 6.2 cubic feet per second.

3. The rate of seepage into the infiltration pipes of the Crystal

Springs Land and Water Company may be mentioned. This system consists of an east-and-west line of infiltration pipes sunk below the normal level of the ground water of the river valley, which join in their lower portion, when they deliver the water collected by them to the surface. The pipes are glazed sewer tile, laid double upon boards in the bottom of a ditch, the space immediately around them being filled with coarse gravel and sand, while above the gravel the cut is filled with material from the excavation. The east infiltration line has a total length of double tile consisting of 1,343 feet of 24-inch tile, 300 feet of 20-inch tile, 1,385 feet of 15½-inch tile, and 619 feet of 12-inch tile, making a total of 3,647 feet of double line. The west infiltration line, also double, has a measured length of 1,721 feet, all of 15-inch pipe.

The water discharged from the system on February 1, 1898, was 9 cubic feet per second, or a mean rate of 0.001677 of a cubic foot per second for each linear foot of length.

Professor King's paper includes the discussion of very many questions of great practical importance—as, for instance, the rate of filtration of water through soil, percolation of water into undisturbed field soil, rate of lateral flow through sands, time required to lower the ground-water level of a system of infiltration pipes, rate of flow of water into wells, flow of water into driven-well points, rate of pumping from driven well compared with rate from open well, and many others which, however, are not referred to here from lack of space. The paper is worthy of close attention from everybody interested in ground water.

The paper also includes a concise summary of what has been done by a number of European observers. A few papers on ground water have appeared since the publication of Professor King's, which, however, the writer has not seen.

In connection with the studies of Professor King, Prof. Charles S. Slichter undertook a theoretical investigation of the motion of ground water, and his paper also appears in the Nineteenth Annual Report of the United States Geological Survey.^a

In this paper Professor Slichter studies the question mostly from the mathematical point of view. As an example of the nature of the problems touched by him the following may be cited:

Given, a uniform bed of unfissured sandstone 100 feet thick, lying between impervious layers and dipping 5 feet per mile; given, further, (a) a uniform temperature of 10° C.; (b) a pore space of 30 per cent; (c) an effective size of grain of 0.15 mm.; (d) an effective head of 10 feet, and, (e) supposing no cementing or clogging material between grains; required, the possible discharge in cubic feet per minute per foot of vertical section into a vertical fissure extending at right angles to the dip and constantly filled with water, when the fissure is 20, 40, 60, 80, 100, 120, 140, 160, 180, and 200 miles from the border of the collecting area.

^aTheoretical investigation of the motion of ground waters, by Prof. Chas. S. Slichter: Nineteenth Ann. Rept. U. S. Geol. Survey (1897-98), Part II.

The rainfall on the catchment area is sufficient to maintain a constant overflow across its border.

The paper concludes with a list of about 80 titles of papers on ground water and related topics.

RELATION OF GEOLOGIC STRUCTURE TO RUN-OFF.

It is somewhat uncertain whether difference in soil due to difference in character of rocks has much influence on the run-off, although casually it appears that sandy soils, from their porousness, do considerably affect the result. Recent studies of this subject have shown (1) that in many river basins the annual run-off stands in a nearly constant relation to the rainfall, and (2) that this constancy is more marked when the excess rainfall above a certain minimum annual depth is considered. This latter statement is equivalent to saying that if the yearly rainfall is less than such minimum depth little or no run-off will take place.

The general truth of this proposition is shown by many Western streams where the run-off is little or nothing. In New Jersey 12 inches of rain during the summer season produce a run-off of 1.5 inches, though others have stated a somewhat different relation. In the State of New York from 1.7 to 2 inches may be considered the general range. As to the amount of rain required to produce any run-off at all, from 12.5 to 16.5 inches have been given. For this minimum many Western streams do not run more than 0.25 to 0.5 inch, and some even are perfectly dry. These statements indicate that the character of the soil, nature of vegetation, the elevation, etc., are of comparatively small importance as regards relation between the yearly volumes of rainfall and run-off. If, however, we consider the rainfall and run-off of the several periods, as shown by the accompanying tables, it is not entirely certain that these propositions are other than approximately true. The weight of evidence indeed is, on the whole, negative. Mr. Vermeule is disposed to attribute nearly all of the differences between streams to difference in geology, and accordingly gives a geologic classification for the New Jersey streams. Mr. Vermeule says:

As a rule, the watersheds which lie upon the same geological formation will be found to have a strong resemblance, both in the character of flow and in the chemical composition of the waters.

Yet, as will be shown later, the Genesee and Oswego rivers, two streams with approximately the same run-off, lie mostly in different geologic formations. As regards quality of soils, Mr. Vermeule also says:

It may be inferred that the kind of soil has much less to do with the amount of evaporation than has the temperature.

As regards the relation between geology and run-off, it is undoubtedly complicated, although it is interesting to note that in the State

of New York streams which flow from the north into Mohawk River, after crossing over a narrow strip of Trenton limestone and Calciferous sand rock, and which head in the Laurentian granite of the Adirondacks, have larger flows than those coming to the Mohawk from the south, which lie mostly in the horizon of the Hamilton shales, the headwaters of some of them—as for instance, Schoharie Creek—being in the sandstones of the Chemung and Portage groups. In their lower reaches they cross over the sandstones and shales of the Hudson and Utica groups, with narrow strips of Helderberg limestone, Oriskany sandstone, and Onandaga limestone.

However, there is another consideration. The headwaters of the streams to the north of the Mohawk nearly all lie in a region heavily timbered—some of it is still primeval forest—while those to the south are from a highly cultivated country, practically deforested.

We may now consider the case of Genesee and Oswego rivers, referring to the large geologic map of the State of New York, published in 1894, by James Hall, in cooperation with the U. S. Geological Survey.

Genesee River has an average rainfall of about 40 inches and Oswego River of about 37 inches. That portion of Genesee River which has been gaged lies almost entirely in the shales and sandstones of the Portage and Chemung groups. Oswego River, on the contrary, lies in the horizon of the Portage sandstones and shales, Hamilton shales, Onandaga and Helderberg limestones, Oriskany sandstone, the rocks of the Salina or Salt group, the Lockport limestone, Clinton limestone and shales, Medina sandstones, and Utica sandstones and shales, including the Oswego sandstone. The Chemung, Portage, and Hamilton formations have a wide outcrop, while the Onandaga, Oriskany, and Helderberg are comparatively narrow bands. The Salina, Lockport, Clinton, and Utica formations are all of considerable extent. Both of these streams are practically without forests, although slight exception to this statement may be noted on the extreme headwaters of the Genesee River in Pennsylvania, where there is still a small area of partially cut forest.

It is an interesting circumstance that the geologic formations in which the Genesee and Oneida rivers lie all have a slope to the south or southwest of from 10 to 30 feet per mile. The main trend of the Genesee River is south and north, while the two main branches of Oswego River—Seneca and Oneida—lie east and west. The Mohawk also flows from west to east. On this basis the Portage, Hamilton, Onandaga, Oriskany, Helderberg, and Salina groups lie mostly south of the Seneca and Oneida rivers, while a portion of the Salina, Niagara, Clinton and Medina groups lie mostly to the north. It is interesting, therefore, to speculate as to whether it is possible that considerable water escapes through these formations, finally appearing far to the south, but in the lack of any certain evidence this must be considered as merely a speculation.

It may be also noted that for tributaries of the Mohawk River lying to the north, the stratified formations—Utica shales, Trenton group, Calciferous sand rock, etc.—slope toward the stream, and hence may be expected, if there is anything in this view, to deliver more water than that merely due to the rainfall of the catchment as measured on the surface.

On the Upper Mohawk there is some evidence that this is true. The limestones here are open, and at several places streams on the surface sink, to reappear, in one case at any rate, with greatly increased volume several miles farther down. Again, at Howe's cave, in Schoharie County, there is a large stream of water flowing in the cave which, so far as known, does not appear anywhere on the surface.

Moreover, the Muskingum River may be referred to. This stream lies in the unglaciated region in southeastern Ohio, mostly in the horizon of the Conglomerate group of the Carboniferous. The main Muskingum River flows generally from north to south, with its main branches to the east and west, that to the west going a short distance into the Waverly group, which is chiefly sandstone and shale, a subdivision of the Carboniferous. The dip is from west to east. In view of the extremely low run-off of this stream, it seems tolerably evident that there can be no material contribution by percolation through these strata.

As other examples of underground flow, the writer may mention Toyah Creek, in Texas, where a stream of (his recollection is) 40 or 50 cubic feet per second flows from the base of a mountain with no indication as to its source. The well-known streams in Mammoth and Luray caves are doubtless familiar to all. There are also a number of river channels in the West where the water sinks into the porous soils, to reappear at some point lower down; but these are hardly allied to the cases under consideration, because the source is here visible.

A stream at Lausanne, Switzerland, may also be mentioned. In 1872 there was a serious epidemic of typhoid fever at Lausanne, Switzerland, which, on investigation, was found to proceed from a brook irrigating lands about a mile distant from a public well, from which the 800 inhabitants of the village mostly took their water supply. Ten years before, or in 1862, a hole had appeared in the channel of the brook at a certain point, 8 feet deep and 3 feet wide, which disclosed at its bottom a running stream, apparently fed by the brook from a point higher up. The brook itself was led into this hole, with the result that the water all disappeared and in an hour or two streamed out at the public well, showing a connection which had been suspected for years. On refilling the hole the brook returned to its bed.

After the epidemic had ceased in 1872 an investigation was held, the hole was reopened and a large quantity of salt thrown in, its pres-

ence in the public well was easily ascertained by a chemical examination.

This case discloses some points of interest. Here was a considerable stream flowing underground which was easily increased from the water of the brook, which was on the surface. Again, the flow here was through coarse gravel.

In the literature of canal construction there are a number of cases cited in which large losses of water have taken place either through coarse gravel or seamy rocks. Doubtless there are numerous other cases, which, however, are not specially important, for it is the writer's intention only to point out, in a general way, reasons why such losses may sometimes take place.

The outflow from Skaneateles Lake has been cited as showing a large loss, presumably by percolation through strata, but on reference to the original authority it is clear enough that an error has been made in so citing it, because the flow measured was really through 9 miles of natural channel and 8 miles of canal, to Montezuma. It may be mentioned that the problem to be determined by this measurement was the discharge into Seneca River and it is quite possible that there may have been a deficiency from the west.

Skaneateles Lake lies at an elevation of 867 feet above tide water and a distance of about 9 miles south of the Erie Canal, for which it has been used as a feeder since 1844. In 1859 Mr. S. H. Sweet made measurements of the flow to the canal and through the same to Montezuma, where the surplus water is discharged into Seneca River, to which it was found to deliver 125 cubic feet per second. Measurements were also made at the foot of the lake, where the flow amounted to 188 cubic feet per second. The loss was 63 cubic feet per second, or one-third of the whole. Skaneateles Lake itself lies in the Hamilton formation, and its outlet, on its way to the Erie Canal, flows across the Onondaga, Oriskany, Helderberg, and Salina formations. The dip is here from north to south, while the stream, which is tributary to the Seneca River, the main westerly branch of the Oswego, flows from south to north, or in the right direction to realize the maximum possible leakage, or percolation, through the strata. Inasmuch as no such leakage is mentioned, it may be reasonably concluded that none occurred.

Cazenovia Lake and Erieville reservoirs are also mentioned, and considerable loss of water is given, which when analyzed is found to be loss of water in the canal, and hence not in any degree attributable to leakage through strata. Cazenovia Lake and Erieville reservoirs both lie south of the Erie Canal, and flow across substantially the same strata as Skaneateles Lake.^a

Such facts as these, while lacking the proof of a scientific demon-

^a Ann. Rept. State Engineer and Surveyor for 1862, pp. 403-404.

stration, are still very interesting and indicate that we have yet much to learn of the peculiarities of stream flow. On the whole, while they undoubtedly point to a moderate loss from percolation, so far as the writer can see they do not indicate any great probability of very large loss from this cause. They do emphasize the fact that every catchment area will have its own formula.

By way of showing that the theory of large evaporation on deforested catchment areas is broadly more reasonable than the theory that there is any great loss of water by seepage owing to inclination of the strata, we may consider the Croton record as given by the appended Table No. 3, where it will be noted that the evaporation from this area is substantially the same as that from Muskingum and Genesee rivers; that is to say, it is the evaporation of a deforested area—the area in forest on this catchment does not exceed 10 per cent. In placing it at 10 per cent the writer means the equivalent in actual effect of dense forest. As regards geologic formation this catchment lies almost entirely in granites and gneisses, in which, from their homogeneous character, it is difficult to assume any loss by percolation through strata. There is, however, a small area of metamorphic Hudson formation, consisting of slate, schist, and quartzite, and also a small area of metamorphic Trenton and Calciferous limestones, but it is exceedingly improbable that any rocks which have been subjected to metamorphic changes are in any degree permeable. This watershed must therefore be considered as underlain by an impermeable formation. All of the water falling upon it except that absorbed by evaporation, chemical changes, etc., reappears as run-off in the streams. It may be safely assumed that there are no other losses. Nevertheless, the evaporation of this stream is that tentatively placed upon other deforested areas. Moreover, there is another interesting consideration of which brief note may be taken at this place. In deference to the water supply department of the city of New York, the writer has used in computing the monthly run-off the catchment area of 338.8 square miles. Mr. Vermeule, however, asserts that this area is not the true one. He says the true area above old Croton dam is 353.1 square miles. If we assume this to be true it follows that the average run-off, instead of being 22.8 inches, is over 4 per cent less, or is, roundly, 21.8 inches. This raises the evaporation from 26.6 inches to 27.6 inches. In his report on forests, Mr. Vermeule has placed the evaporation of his second Croton series, which the writer understands him to consider more reliable, at 22.6 inches, a difference of 5 inches from the foregoing figures, which it may be remarked is based upon the latest revision and is presumably more likely to be correct.

The catchment area of Lake Cochituate may be mentioned. According to Mr. FitzGerald, the slopes of the Cochituate catchment are flat and sandy, with a surface of mostly modified drift. The average rainfall for twenty-nine years, from 1863 to 1891, is 47.1 inches,

the average run-off 20.3 inches, and the evaporation for this period 26.8 inches. This evaporation places it at once in the category of deforested streams. Probably the equivalent of dense forest does not exceed 5 per cent.

The catchment area of Sudbury River has steeper slopes than that of Lake Cochituate and is largely composed of unmodified drift. The rainfall for twenty-six years is 1 inch less than on the Cochituate catchment, and the run-off 2.3 inches larger. The amount of forest does not exceed 6 to 8 per cent. Neshaminy Creek flows from north to south, emptying into the Delaware River not far from Bristol. For several miles its headwaters flow from west to east. Perkiomen Creek flows from north to south, and enters the Schuylkill River about 7 miles above the city of Norristown. Tohickon Creek flows from west nearly due east, although somewhat crooked for a few miles, then flowing in a southwesterly direction it reaches the Delaware River.

The surface of the ground is mostly farm land under a high degree of cultivation. The original forest growth has been almost entirely cut away, and the little remaining timber is found generally on the banks of the creeks, where the hillside is too steep to be cultivated, or on a few patches of bottom land. This growth is mostly composed of hickory, chestnut, oak, and ash. Even this is fast disappearing to supply the ever-increasing demand for railroad ties, fence posts, and rails. The proportion of cultivated lands, woodlands, etc., is as follows: Woodland, about 20 per cent; cultivated land, about 77.5 per cent; roads, 2 per cent, and flats, 0.5 per cent.^a

On the upper Hudson River, with a catchment above Mechanicville of 4,500 square miles, the average rainfall for the fourteen years from 1888 to 1901, inclusive, was about 44.2 inches, the average run-off 23.3 inches, and the evaporation 20.9 inches. Above Glens Falls this stream lies almost entirely in the pre-Cambrian gneiss, from which it is improbable that there is any loss of water. Its main tributary to the west, Sacandaga, is, by observation, an exceedingly prolific water yielder. To the east, the Battenkill and Hoosic rivers have a different geologic history. The Battenkill flows across the Hudson shales, the Georgia limestones and shales, finally rising in the metamorphic Hudson and Trenton formations. The Hoosic River has a similar geologic history. The run-off of the Hoosic River is, without doubt, considerably less than that of the main Hudson. The average precipitation in western Massachusetts from 1887 to 1895, inclusive, was 38.98 inches, as against 43.29 inches in the northern plateau from 1889 to 1895, inclusive, a difference of 4.31 inches. Should such difference continue, the run-off of Hoosic River might be expected to be, on an average, about 20 inches. Moreover, the Hudson River above Glens Falls (catchment about 2,800 square miles) is still largely in forest—probably about 85 per cent—but on

^aCodman, John E., Observations on rainfall and stream flow in eastern Pennsylvania: Proc. Engrs. Club of Phila., Vol. XIV, No. 2, July-Sept., 1897.

the catchments of Wood Creek, Battenkill, and Hoosic rivers the proportion of forest is very much less—as an offhand estimate, the writer would say perhaps 20 to 30 per cent. The run-off of Schroon River, which is perhaps 70 per cent of an equivalent to fairly dense forest, is for four years 26.84 inches. There is, however, some doubt whether this record is entirely reliable, and for the present it is not intended to more than merely call attention to the general proposition that this stream, which issues from an impermeable watershed with 70 per cent of its catchment in forest, has a rather large run-off. The whole catchment area of the Upper Hudson of about 4,500 square miles, will probably not exceed 50 to 60 per cent of forest.

The following are the catchment areas of the several streams here considered: Hoosic, 711 square miles; Battenkill, 438 square miles; Sacundaga, 1,057 square miles, and Schroon River, 570 square miles.

The Pequannock River may also be referred to. This stream is characterized by sharp slopes throughout its whole extent. Its headwaters are at an elevation of about 1,500 feet, while the mouth is only 170 feet above tide. The catchment is about 14 to 16 miles long by 4 to 7 miles wide. Mr. Vermeule states that its headwaters lie in the pre-Cambrian highlands. The sharp slopes, combined with small catchment area, undoubtedly account for the relatively large run-off of this stream. There is also an uncertainty of 1 or 2 inches in the rainfall record. The catchment is judged by the writer to be 70 per cent forest.

In riding over the Pequannock catchment several times the writer was much struck by the fact that aside from the main valleys there are no gulleys throughout this area. The record shows that precipitation is frequently very heavy, but it has been thus far without effect. The indications appear to be that the rainfall, however intense it may be, sinks almost entirely into the ground, and without doubt this peculiarity has its effect on the run-off.

It may be pointed out that the geology of Muskingum and Genesee rivers is substantially the same, while the geology of Croton River and that of Lake Cochituate are entirely different. Nevertheless, when analyzed by aid of the diagrams (figs. 12-16, inclusive), these streams are seen to all have substantially the same evaporation and run-off, although the rainfall on Croton River and Lake Cochituate is different from that of Muskingum and Genesee rivers. Hudson River, however, which has much the same geology as Croton River and Lake Cochituate, has still a very different run-off and evaporation. Oswego River, which lies in a different formation from Genesee River, has still nearly the same evaporation.^a

These several facts favor the view that deforestation is the real cause of the smaller run-off of Muskingum, Genesee, and Croton rivers and Lake Cochituate.

^aThe evaporation of Oswego River is, in fact, a little greater, due to the existence of large marsh areas on Oswego River.

EFFECTS OF FORESTS.

DO FORESTS INCREASE RAINFALL?

The evidence on this point is conflicting. The variation of the observed from the true rainfall being so great, as has just been shown, the answer to this question must be regarded as very uncertain. It has been discussed by Professor Abbe and Dr. Hough.^a The following summation by Dr. Hough, although made 26 years ago, may be accepted as expressing the fact at the present day.

The reciprocal influences that operate between woodlands and climate appear to indicate a close relation between them. It is observed that certain consequences follow the clearing off of forests, which can scarcely be otherwise regarded than as a direct effect, such as the diminution of rivers and the drying up of streams and springs. Other effects, scarcely less certain, are seen in the occurrence of destructive floods, and of unseasonable and prolonged droughts, with other vicissitudes of climate which it is alleged did not occur when the country was covered with forests. These appear to have been brought about by their removal, and might, in a great degree, be alleviated by the restoration of woodlands to a degree consistent with our best agricultural interests.

On the other hand, there are many facts tending to show that the presence or absence and the character of forests are the effect of climate, and that their cultivation generally, or the planting of particular species, is closely dependent upon it. These conditions of climate should be understood before forest cultivation is attempted. It is also to be noticed that differences of opinion have been expressed among men of science as to the extent of influence that forests exert upon the climate, and it is quite probable that the advocates of extreme theories may have erred on both sides. But where principles depend upon facts that may be settled by observation, there should be no differences of opinion; and as there is no fact in this subject that may not be verified or disproved, the existence of such differences only shows the want of accepted evidence derived from trustworthy records.

The interested reader is referred to Dr. Hough's report, which may be easily obtained, for an extended discussion on this point.

EFFECTS OF FORESTS ON RUN-OFF.

The extent of forestation has probably a considerable effect on the run-off of streams. With similar rainfalls, two streams, one in a region having dense primeval forests, the other in a region wholly or partially deforested, will show different run-off. The one with the dense forests will show larger run-off than the stream in the deforested area. In some parts of the State of New York these differences may amount to as much as 5 or 6 inches in depth over the entire catchment area. Yet it must be said that this proposition is, for the present, tentative in its character.

The writer is particular to specify dense forests, because a good deal of discussion has clustered around this point. Of such forests,

^aReport upon forestry, by Franklin B. Hough, U. S. Department of Agriculture (1877).

the most effective are those composed of spruce, pine, and other evergreen trees. Where the forest is more or less open to wind and sunshine, its effect, while considerable, is still much less marked than that of dense evergreen forests where the sun seldom penetrates and the wind effect, even in a gale, is only slight. On a catchment area where there are only scattered patches of forest, the effect is practically the same as on a deforested area. The same proposition is generally true on a catchment with young trees. What is wanted for the maximum effect is a mature evergreen forest.

This proposition, however, though definitely stated here, has been nevertheless the subject of considerable discussion, and owing to its complex nature, it is improbable that a final conclusion concerning it will very soon be reached. The writer has discussed this subject in various papers, which may be referred to for details that are mostly omitted here.^a

WHY THE REMOVAL OF FORESTS AFFECTS STREAM FLOW.

Whatever question there may be as to the influence of forests on rainfall, there is, in the opinion of the writer, none as to such influence on stream flow. Yet this proposition has also been discussed pro and con and is likely to give rise to further discussion, and the conclusion will, therefore, for the present be considered tentative in its character.

It seems to the writer that the removal of forests decreases stream flow by allowing freer circulation of the air and by causing higher temperature and lower humidity in summer and so producing greater evaporation from water surfaces, as well as from the ground.

^a The following reports and papers are cited:

1. Three reports on Genesee River storage surveys: Appendixes to Ann. Repts. State Engineer and Surveyor for 1893, 1894, and 1896.
2. Two reports on Upper Hudson storage surveys: Appendixes to Ann. Repts. State Engineer and Surveyor for 1895 and 1896.
3. Water supply of the western division of the Erie Canal: Ann. Rept. State Engineer and Surveyor for 1896.
4. The economics of the Hudson River; lecture before the engineering classes of Rensselaer Polytechnic Institute, Feb. 24, 1897.
5. Stream flow in relation to forests: Proc. Am. Forestry Association, Vol. XII, 1897; also, reprint in Ann. Rept. Fisheries, Game and Forest Commission (1896), published in 1898. Reprint, 1898.
6. Natural and artificial forest reservoirs of the State of New York: Third Ann. Rept. Fisheries, Game, and Forest Commission (1897), published in 1899. Reprint, 1899.
7. Water Resources of the State of New York, Parts I and II: Water-Supply and Irrigation Papers U. S. Geol. Survey, Nos. 24 and 25, 1899.
8. On the application of the principles of forestry and water storage to the mill streams of the State of New York: Proc. Twenty-second Ann. meeting of Pulp and Paper Association. (1899.)
9. Indian River dam, by Geo. W. Rafter, Wallace Greenalch, and Robert E. Horton: Engineering News, May 18, 1899. Reprint, 1899.
10. Data of stream flow in relation to forests; lecture before engineering classes of Cornell University, April 14, 1899: Trans. Association of Civil Engineers of Cornell University, Vol. VII, 1899. Reprint, 1899.
11. A report on a water supply from the Adirondack Mountains for the city of New York; Appendix E of an inquiry into the conditions relating to the water supply in the city of New York by the Merchants' Association, 1900.
12. Report to the Board of Engineers on deep waterways, on the water supply of enlarged canals through the State of New York; Appendix 16, pp. 571-950. (1901.)

That the removal of forests renders stream flow less equal throughout the year and so causes floods and periods of dryness in rivers seems to be beyond reasonable question, for the forest litter and root masses serve as storage reservoirs, tending to equalize the flow of streams.

Space will not be taken to discuss these propositions, because very little can be added to previous discussions. The reader is referred to the Bulletin No. 7, of the Forestry Division of the Department of Agriculture on Forest Influences, as well as to Dr. Hough's report on forests, for fairly complete discussions.

FORESTATION OF THE CROTON CATCHMENT AREA.

In a paper^a read before the American Forestry Association in 1901, Mr. Vermeule proposes the question whether the forestation of the catchment area of the Croton water supply is advisable. In considering this question it may be pointed out that if the Croton watershed were forested, there is no probability of reaping the full benefit under from 75 to 150 years. On this point the following statement by Mr. B. E. Fernow, director of the New York State College of Forestry, at Cornell University, is pertinent:^b

The one thing in which the forestry business differs from all other business is the long-time element, for it takes 100 years and more to grow trees fit for the use of the engineer, the builder, and the architect; hence the dollar spent now in its first start must come back, with compound interest, 100 years hence.

For the sake of the argument, we will assume that on this watershed in 120 years the full effect of forestation would be realized. This would give, as an average, an increase of from 4 to 6 inches in run-off. For the purposes of this discussion we may assume it at 5 inches.

In order to forest the watershed it would be necessary to acquire the entire area, which, so far as the writer can ascertain, could hardly be done for less than \$100 per acre. Probably the price would be much greater than this, but to avoid an overestimate it may be fixed at \$100 per acre. At this rate the catchment area of 339 square miles would cost \$21,696,000. The planting out of trees could hardly cost less than \$20 per acre additional, but in order to make the estimate as reasonable as possible we will take it at \$10 per acre, which makes an additional sum of \$2,169,900, or a total of \$23,865,900.

If we assume the annual interest at 3 per cent, and place this sum at compound interest for 120 years, we have at the end of that time the sum of \$779,510,000. The present safe yield of the Croton watershed, with all available storage, is about 280,000,000 gallons per day. We would pay, therefore, this large sum for, perhaps, 75,000,000 gallons additional per day at the end of 120 years. It is true, there

^aNew Jersey forests and their relation to water supply, by C. C. Vermeule: The Engineering Record, Vol. XLII, No. 1 (July, 1901).

^bThe forester an engineer, by B. E. Fernow: Jour. Western Soc. Engrs., Vol. VI, No. 5 (Oct., 1901).

would be some increase in water supply after about 30 years, and the supply might be expected to go on increasing until the average increase of yield was attained in 120 years. But the increase in water supply would not be at all commensurate with the increase of capitalization. It is very evident that an expenditure of this sum of money would procure a far greater quantity of water from other sources. Hence it does not seem expedient to suggest the forestation of the Croton catchment area.

Another objection to the forestation of the Croton watershed as a remedy for the water difficulties of New York City may be found in the fact that a considerably increased water supply is wanted at once; it is entirely out of the question to wait 120 years for such increased supply.

As a broad proposition, however, catchment areas from which municipal water supplies are drawn should be in forests, and undoubtedly as time goes on this condition will be more and more attained. Already various European and American municipalities have recognized the advisability of owning the catchments from which their municipal water supplies are drawn.

DETAILS CONCERNING TABLES AND DIAGRAMS.

TOPOGRAPHIC RELATIONS OF CATCHMENT AREAS OF STREAMS TABULATED.

The following gives an outline of the topography of the several catchment areas included in the tables.

The headwaters of Muskingum River lie at an elevation of about 1,100 feet, and it flows into the Ohio River, near Marietta, at an elevation of about 500 feet. The Muskingum River proper has a length of 109 miles, with its main tributaries, the Walhonding and the Tuscarawas, having an additional length of about 100 miles, thus giving the basin a length of 200 miles. From the head of the Tuscarawas to the junction of the two main tributaries there is a fall of about 2 feet per mile, and from this point to the mouth of the main Muskingum the descent is about 1.5 feet per mile. On the Walhonding the descent is more rapid. At its headwaters, near Mansfield, the stream is from 400 to 450 feet above what it is at its junction with the Tuscarawas.

The Genesee River rises in Potter County, Pa., and flows in a northerly direction across the State of New York, emptying into Lake Ontario at Rochester, having a total length of about 115 miles. Its headwaters are at an elevation of over 2,000 feet, while Lake Ontario lies at a mean elevation of 247 feet. This stream is specially characterized by two sets of falls. The three falls at Portage have an aggregate of about 270 feet, while at Rochester the river falls 263 feet, also in three falls, with some intervening rapids. This stream flows for several miles at Rochester and Portage over bare rocks.

The Croton River flows into the Hudson at Croton Landing at an elevation of practically tide water. Its extreme headwaters in Dutchess County are at an elevation of about 700 feet above tide. Its length is about 35 miles.

Lake Cochituate is in a generally flat area at an elevation of about 200 feet above tidewater. A small area in the south portion rises to an elevation of 300 feet. The greatest extent of this area is from northeast to southwest, about $9\frac{1}{2}$ miles, with an average width of about 2 miles. In the northern part it is narrower than this and in the southern somewhat greater.

Sudbury River catchment area lies immediately to the west of the Lake Cochituate catchment. The elevations vary from about 200 feet above tide to from 500 to 600 feet. Its length from north to south is about 10 miles, and from east to west about 8 miles. Owing to a number of hills throughout the area the slopes are much steeper than on the Cochituate catchment. Sudbury catchment lies about 25 miles to the west of Boston.

Mystic Lake is practically at sea level, with considerable hills in a portion of the catchment area. The slopes are steep, but not quite as steep as Sudbury.

Neshaminy Creek flows into the Delaware River at an elevation of from 10 to 20 feet above tide water. Its headwaters are at an elevation of about 300 feet. Its extreme length from north to south is from 40 to 45 miles.

Perkiomen Creek flows into the Schuylkill at an elevation of about 75 feet above tide level. The headwaters are at an elevation of 550 feet. The length of the basin from north to south is about 30 miles.

Tohickon Creek flows into the Delaware River at an elevation of about 70 feet above tide. Its extreme headwaters are at an elevation of 525 feet. Its length, from east to west, is about 25 miles.

Hudson River, at Mechanicville, is about 60 feet above tide, while at its extreme headwaters it is about 3,400 feet above tide level. The catchment area above Glens Falls is from 40 to 50 miles from east to west and from 60 to 65 miles from north to south. Below Glens Falls the catchment extends well into southern Vermont and Massachusetts. The length of the stream above Mechanicville is from 120 to 125 miles.

Pequannock River flows into the Passaic near Pompton, at an elevation of 170 feet above tide. The main facts of the topography of this stream have been given in the chapter on "The relation of geology to the run-off of streams."

The Connecticut River flows into Long Island Sound at tide water, and rises in the northern part of New Hampshire. Its extreme headwaters issue from an elevation of 2,000 to 3,000 feet above tide level. Its length is about 375 miles. The topography of this catchment is hilly and, in the northern part, mountainous.

CLASSIFICATION OF STREAMS.

In Table No. 13 we have the mean rainfall, run-off, and evaporation of the storage, growing, and replenishing periods of the streams for which individual figures are given in Tables Nos. 1 to 12, inclusive. This table shows what may be termed the family resemblance between streams. For instance, for the Muskingum and Genesee rivers the mean rainfall of the storage period is about 19 inches, with a run-off of about 10 inches and an evaporation of about 9 inches. For the growing period the mean rainfall of each of these two streams is about 12 inches, with run-off 1.7 inches and evaporation 10 inches. For the replenishing period the mean rainfall of each is about 9 inches, with run-off about 2 inches and evaporation 7.5 inches. The total rainfall of the whole year is 40 inches for each stream—run-off 13.5 inches and evaporation 26.5 inches.

The Croton River has a much higher rainfall. Twenty-four inches in the storage period produces 17 inches of run-off, with an evaporation of 7 inches. From 13.6 inches of rain in the summer we have 2.6 inches of run-off, with 11 inches of evaporation. The rainfall for the year is 49.4 inches, or, say, 9 inches more than for Muskingum and Genesee rivers. The run-off is also about 9 inches in excess of that of these two streams. The evaporation is, however, the same, pointing very strongly to a similar cause.

On Lake Cochituate catchment 23.1 inches rainfall in the storage period produces on an average but 14.9 inches of run-off, with 8.2 inches of evaporation. The rainfall of the growing period is the same as that of the Muskingum and Genesee rivers, yielding, however, 2.1 inches run-off and 9.5 inches evaporation. For the replenishing period, 12.4 inches rainfall yields 3.3 inches run-off, with 9.1 inches evaporation. The totals for the year are, rainfall, 47.1 inches; run-off, 20.3 inches, and evaporation, 26.8 inches. Aside from difference in catchment areas, the total evaporation of both Croton River and Lake Cochituate is substantially the same as that of Muskingum and Genesee rivers. The excess rainfall of Lake Cochituate over Muskingum and Genesee rivers is about the same as the excess evaporation; that is to say, 7.5 inches. As regards evaporation, Lake Cochituate may therefore class with the Muskingum, Genesee, and Croton rivers.

For Sudbury River, Mystic Lake, Neshaminy and Perkiomen creeks, somewhat different conditions prevail. The yearly evaporation is here about 24 inches, and, with the exception of Mystic Lake, the run-off is about 23 inches. On Mystic Lake catchment the rainfall is enough smaller to fully account for the difference in run-off. Broadly, these four streams may be considered as making a second class.

Tohickon Creek has a total annual mean rainfall of 50 inches, from whence it results that the mean yearly run-off is 28.4 inches and the

evaporation 21.7 inches. This stream varies so much, from what the general principles indicate, that the writer doubts somewhat the correctness of the record. He considers it quite possible that it may be 10 per cent to 20 per cent in error. Reasons for this view are given in the chapter on "Negative evaporation." The writer recognizes, however, that in view of the uncertainty of gagings, etc., the mere fact of a stream not squaring with preconceived views ought not to condemn its record. There must be valid reasons for rejecting the particular record.

The Hudson River shows apparently the effect of an impermeable catchment, combined with a large forest area. It has a mean annual rainfall of 44.2 inches, yielding 23.3 inches run-off, with 20.9 inches evaporation. For the storage period 20.6 inches rainfall yields 16.1 inches run-off, with 4.5 inches evaporation. For the growing period 12.7 inches rainfall yields 3.5 inches run-off, with 9.3 inches evaporation. For the replenishing period 10.9 inches rainfall yields 3.7 inches run-off and 7.1 inches evaporation. This stream, from general similarity, may properly classify with the Connecticut.

For the Pequannock River explanations have already been given, which apply generally. For the present it tentatively stands in a class by itself.

The classification here given is experimental merely, and is subject to modification with the gathering of more complete data.

DESCRIPTION OF TABLES NOS. 1 TO 12.

Table No. 1 gives the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods, as well as the total of these three items, on the Muskingum River, for the years 1888-1895, inclusive. The minimum year was 1895, the total run-off being 4.90 inches. The maximum occurred in 1890, with a total run-off of 26.84 inches. The mean run-off for the entire period is 13.1 inches.

Table No. 2 gives the same facts for the Genesee River for the years 1890-1898, inclusive. In this table, for the years 1890-1892, the record of Oatka Creek, which was gaged by the writer, has been used. For a portion of 1893, the results are computed. The dam at Mount Morris, at which gagings were taken, was carried away by a flood early in 1897, and for the years 1897 and 1898 the gaging record has been deduced by comparison of the rainfalls with those at Rochester, where gagings are kept by the city engineer. The results, aside from those for the years 1894-1896, must be considered somewhat approximate, although probably within 10 per cent of the truth. The mean evaporation for the years 1894-1896 was 27.21 inches.

Table No. 3 exhibits the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods for Croton River, from 1868-1899, inclusive, a period of thirty-two years. This record has

been revised as per experiments at Cornell University, described by John R. Freeman, member American Society Civil Engineers, in his report to the comptroller in 1900. As shown by Mr. Freeman, the rainfall record from 1868-1876, inclusive, is not very reliable, and accordingly two sets of means are given. The mean rainfall from 1868-1876, inclusive, was 45 inches, the mean run-off 23.37 inches, and the mean evaporation 21.63 inches. For the second period the rainfall from 1877-1899, inclusive, has been so rationally treated by Mr. Freeman as to leave nothing to be desired. The means for this second period are: rainfall, 49.33 inches; run-off, 22.81 inches, and evaporation, 26.52 inches. A comparison of these two sets of means shows how dangerous it is to draw final conclusions from data about which there is considerable doubt. The rainfall differs by 4.33 inches and the evaporation by 4.89 inches, or from 20 per cent to 25 per cent.

In preparing this table the figures of table No. 26 of Mr. Freeman's report have been used. This table is in million gallons per 24-hour day, and has been reduced to inches per month on the catchment area of 338.8 square miles. The following gives the water surfaces exposed to evaporation at different periods:

	Per cent.
5.8 square miles, 1868-1873,	= 1.73
6.2 square miles, 1873-October, 1878,	= 1.83
6.9 square miles, 1878-1891,	= 2.03
8.4 square miles, 1891-1893,	= 2.48
9.5 square miles, 1893-1895,	= 2.82
11.0 square miles, 1895-1897,	= 3.28
12.0 square miles, 1897-1900,	= 3.56

It may at first thought be imagined that these large water surfaces exposed to evaporation have considerably increased the ground evaporation over the entire catchment. When, however, one considers that it is only the difference between what a water-surface evaporation and what a ground-surface evaporation would be, the difference is seen to be not very much. For instance, assuming the water-surface evaporation at 36 inches per year and the ground-surface evaporation at 27 inches per year, the difference becomes 9 inches. With 12 square miles of water surface in 1900, giving 3.56 per cent of the whole, the excess of water-surface evaporation over ground-surface evaporation is 0.32 of an inch, a quantity which is so far within the limit of possible error in other directions as to be negligible. At the most, taking the assumed catchment area at 338.8 square miles, it would only reduce the evaporation from 26.5 inches to 26.2 inches.

The minimum year in this table is seen to be 1880, when only 13.71 inches ran off. In 1883 the run-off was also very low, being only 13.74 inches.

Table No. 4 exhibits a similar set of facts for Lake Cochituate from 1863-1900, inclusive. Two sets of means are also given in this case,

one from 1896-1900, a period of 5 years, and the other from 1863-1900, a period of 38 years. There is very little difference between these two sets of means. The minimum year is seen to have been 1883, when there was only 10.09 inches of run-off.

Table No. 5 gives the same data for Sudbury River from 1875-1900, inclusive, a period of 26 years. Two sets of means, one for the five years from 1896-1900, inclusive, and the other for the entire period of 26 years, are also given in this case. The catchment area of this stream is hilly, and considerable variation in rainfall may be expected to take place. Originally only one rain gage was exposed, but latterly there are several, and the rainfalls as given in the table are the means of these. In 1883, which was the year of minimum run-off, only 11.40 inches appeared in the stream, out of a total precipitation of 31.52 inches.

According to the Sixth Annual Report of the Metropolitan Water Board, rainfall observations for Sudbury catchment were taken as follows: January, 1875, to April, 1876, Lake Cochituate only; April to June, 1876, Lake Cochituate, Westborough, and Hopkinton; June to December, 1876, Lake Cochituate, Southborough, Marlborough, Westborough, and Hopkinton; December, 1876, to January, 1883, Framingham, Southborough, Westborough, Marlborough, and Hopkinton; January, 1883, to January, 1884, Framingham and Southborough; January, 1884, to January, 1890, Framingham and Westborough; January, 1890, to May, 1898, Framingham and Ashland dam; June, 1898, to December, 1900, Framingham, Ashland dam, Cordaville, and Sudbury dam.

The catchment area of Sudbury River, from 1875-1878, inclusive, was 77.764 square miles; in 1879 and 1890 it was 78.238 square miles, and from 1881-1900, inclusive, 75.2 square miles.

On Sudbury catchment water surfaces were 1.9 per cent of the whole from 1875-1878, inclusive; they were 3 per cent in 1879, 3.4 per cent in 1885, 3.9 per cent in 1894, and 6.5 per cent in 1898. The catchment also contains extensive areas of swamp land, which, although covered with water at times, are not included in the above percentages of the water surfaces.

Table No. 6 gives the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods for Mystic Lake catchment, from 1878-1895, inclusive, a period of 18 years. The minimum year, with a total run-off of 9.44 inches, occurred in 1883. Since it is the run-off of the minimum year which determines the value of a stream for water supply, this figure shows that this stream is not, on the whole, as good a water yielder as Lake Cochituate and Sudbury catchments.

Table No. 7 gives the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods for Neshaminy Creek for the

years 1884–1899, inclusive, a period of 16 years. The minimum year was 1895, when, with a rainfall of 38.59 inches, 18.15 inches ran off. Neshaminy Creek may be taken as a deforested area.

Table No. 8 gives for Perkiomen Creek the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods for the 16 years from 1884–1899, inclusive. The minimum year was 1895, when, with 40.35 inches rainfall, the run-off was 17.58 inches. The writer's recollection is that in riding through this area some time ago, the forest is mostly scattered and is probably equivalent in effect to not more than 8 per cent to 10 per cent of dense forest. If he is wrong in this, he will be glad to be set right.

Table No. 9 gives for Tohickon Creek the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods from 1884–1898, inclusive, a period of 15 years. The year of minimum run-off was 1896, when 48.03 inches of rainfall yielded 19.73 inches of run-off. The rainfall of this catchment is considerably higher than that of the two contiguous streams, from whence it results that the run-offs are also larger.

Table No. 10 gives the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods for the Hudson River area for a period of 14 years, from 1888–1901, inclusive. The minimum year was 1895, when 36.67 inches of rainfall yielded 17.46 inches as run-off in the stream.

Table No. 11 gives the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods of the Pequannock River catchments for 9 years, from 1891–1899, inclusive. The minimum year was 1895, when, with 37.92 inches of rainfall, 21.11 inches appeared as run-off. The rainfall record for this catchment area is not entirely satisfactory and further study may modify it somewhat.

Table No. 12 gives the rainfall, run-off, and evaporation of the storage, growing, and replenishing periods for the Connecticut River at Hartford for a period of 14 years, from 1872–1885, inclusive. The minimum year was 1883, when, with 32.55 inches of rainfall, 12.61 inches ran off. The record, however, of the year 1883 is that of Holyoke, Mass., the years 1882 and 1883 not being given in Mr. Babb's paper, from which these data are otherwise taken. For these years the rainfall has been computed and is, of course, approximate.

Moreover, the record of Connecticut River as a whole can not be deemed very satisfactory, either as regards the rainfall or the run-off. The run-off is probably anywhere from 5 per cent to 20 per cent in excess and a considerably larger number of stations should be averaged to give safe rainfall. The record at Holyoke from 1880–1899, inclusive, is considered much more satisfactory, but unfortunately this record is not accompanied by the rainfall, and thus far the writer has not had an opportunity to obtain these.

DESCRIPTION OF DIAGRAMS

We may now consider a few of the large number of diagrams which have been prepared.

Fig. 1 shows, for the Upper Hudson, precipitation, evaporation, run-off, and mean annual temperature for the years 1888-1890, inclusive, plotted in the natural order.

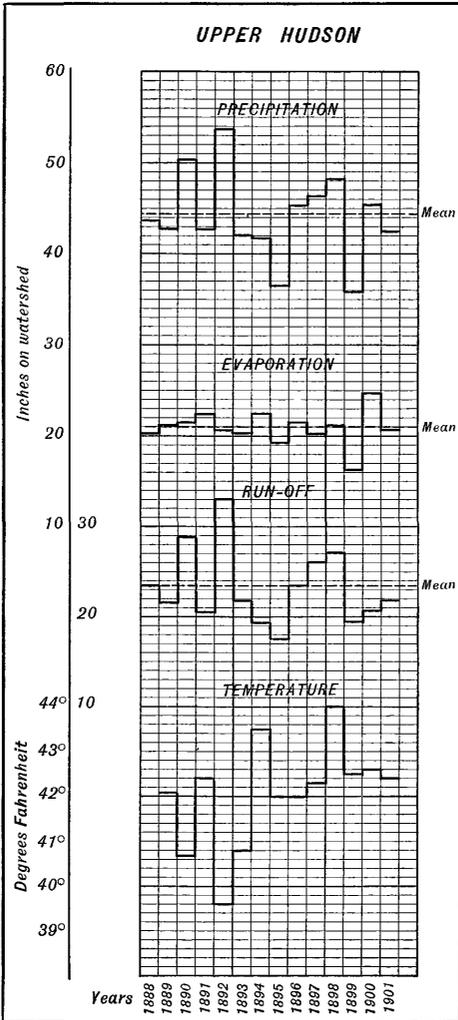


FIG. 1.—Diagram showing relation between precipitation, evaporation, run-off and temperature on the Upper Hudson River.

Fig. 2 shows, for the same area, evaporation and mean annual temperature, plotted in the order of the evaporation.

Fig. 3 shows, for the Upper Genesee, precipitation, evaporation, run-off, and mean annual temperature, plotted in the order of the precipitation.

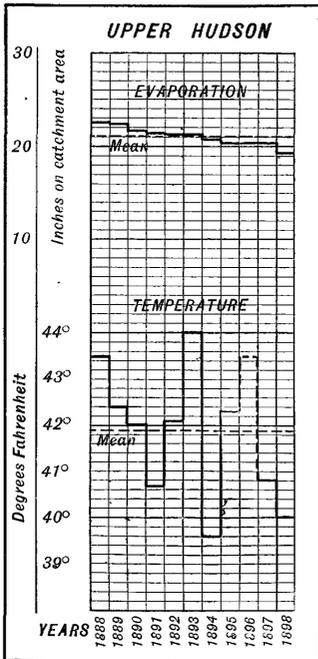


FIG. 2.—Diagram showing the relation between evaporation and temperature on the Upper Hudson River, the years being arranged according to the amount of evaporation.

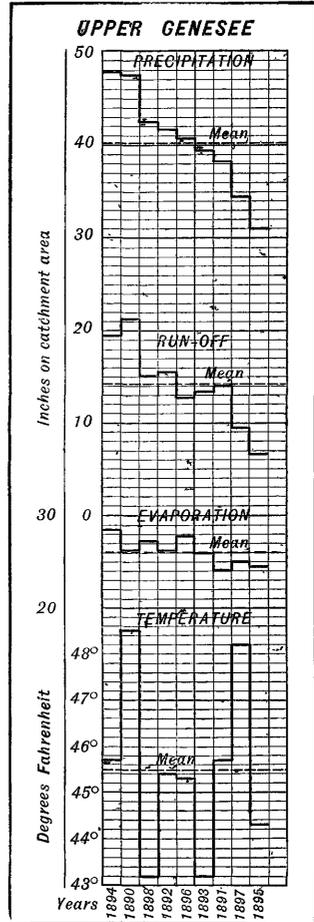


FIG. 3.—Diagram showing the relation between precipitation, run-off, evaporation, and temperature on the Upper Genesee River, the years being arranged in order of dryness.

Fig. 4 shows, for Sudbury River, precipitation, evaporation, run-off, and mean annual temperature, plotted in the natural order.

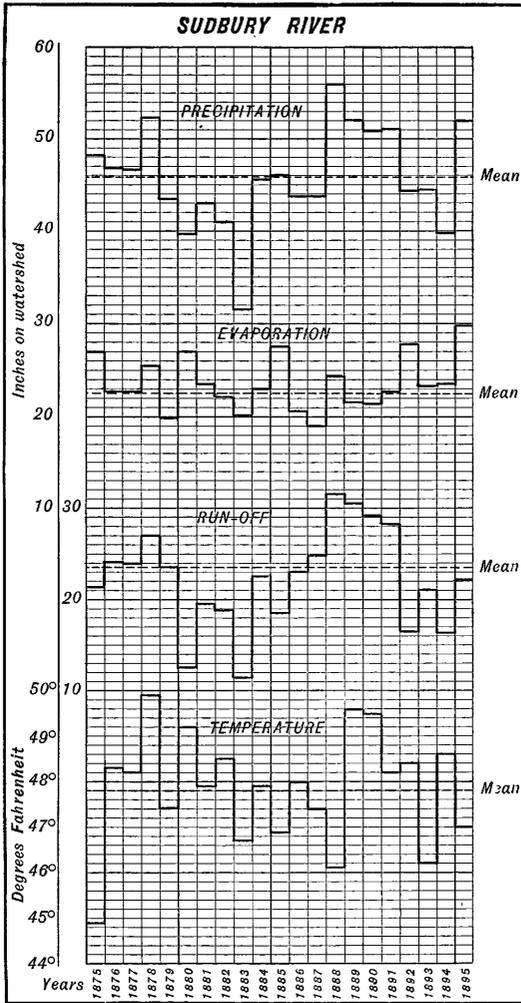


FIG. 4.—Diagram showing the relation between precipitation, evaporation, run-off, and temperature on the Sudbury River, Massachusetts.

On fig. 5 we have, for the same stream, precipitation, evaporation, run-off, and mean annual temperature, plotted in the order of the precipitation.

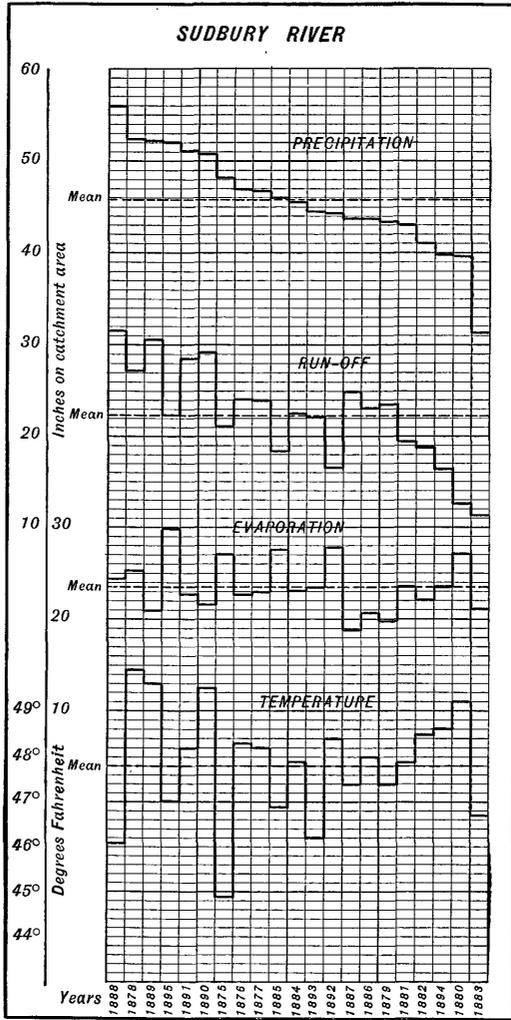


FIG. 5.—Diagram showing relation between precipitation, evaporation, run-off, and temperature on the Sudbury River, Massachusetts, the years being arranged in order of dryness.

On fig. 6 we have, also for Sudbury River, evaporation and mean annual temperature, plotted in the order of the evaporation.

Fig. 7 shows, for the Muskingum River, precipitation, evaporation, run-off, and mean annual temperature, plotted in the order of the precipitation.

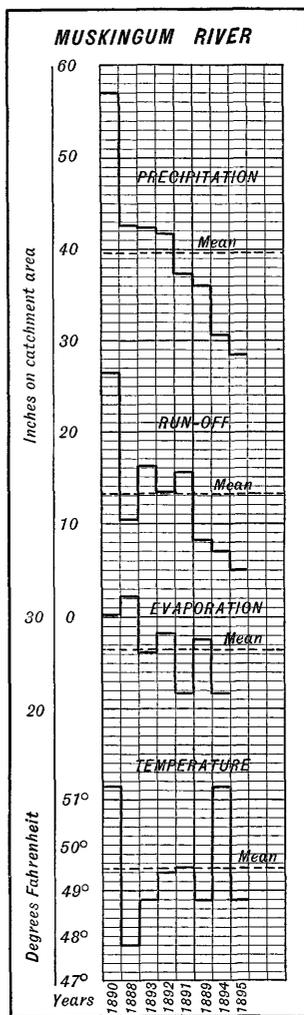
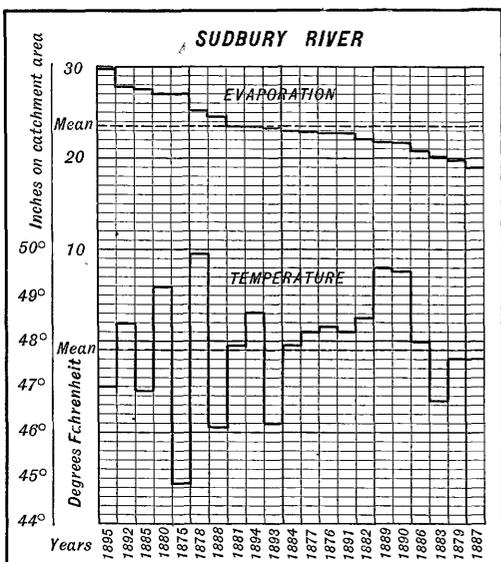


FIG. 6.—Diagram showing the relation between evaporation and temperature on the Sudbury River, the years being arranged according to the amount of evaporation.

FIG. 7.—Diagram showing the relation between the precipitation, run-off, evaporation, and temperature on the Muskingum River, Ohio, the years being arranged in order of dryness.

Fig. 8 shows, for Lake Cochituate, precipitation, evaporation, run-off, and mean annual temperature, plotted in the order of the precipitation.

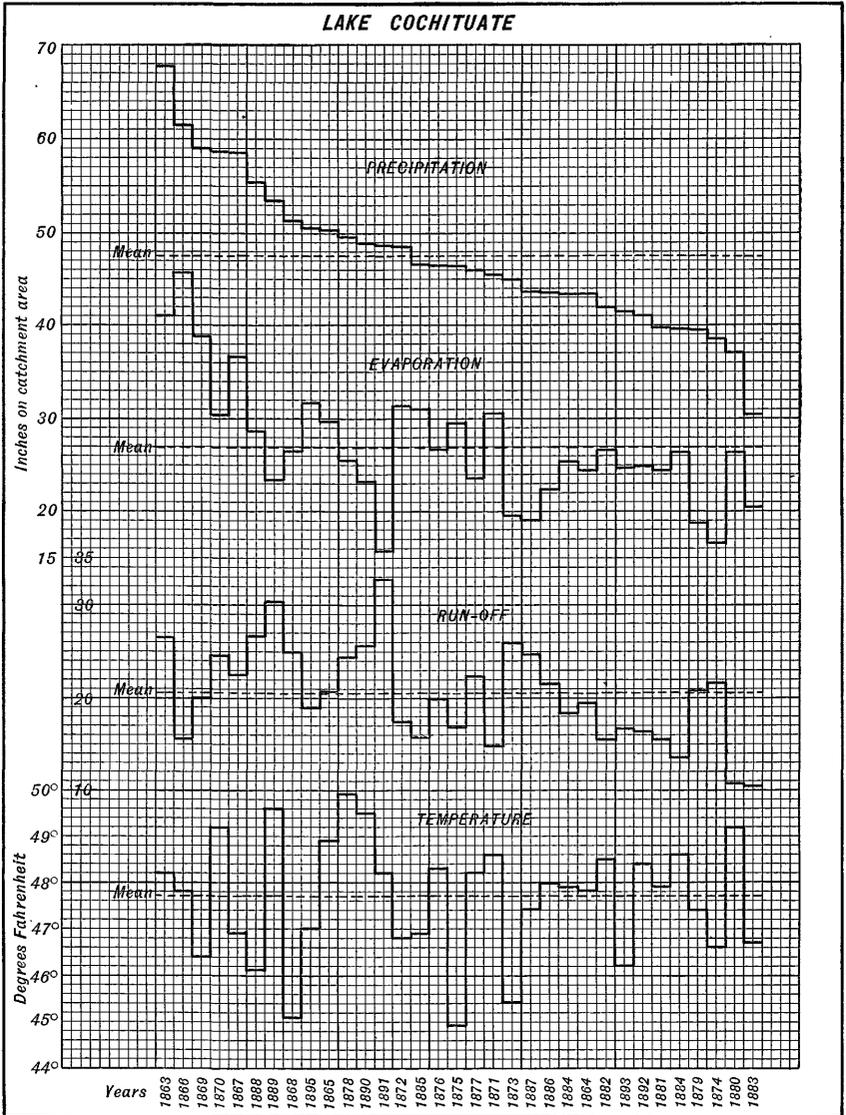


FIG. 8.—Diagram showing the relation between the precipitation, evaporation, run-off, and temperature in the Lake Cochituate Basin, the years being arranged in order of dryness.

Fig. 9 shows, for Lake Cochituate, evaporation and mean annual temperature, plotted in the order of the evaporation.

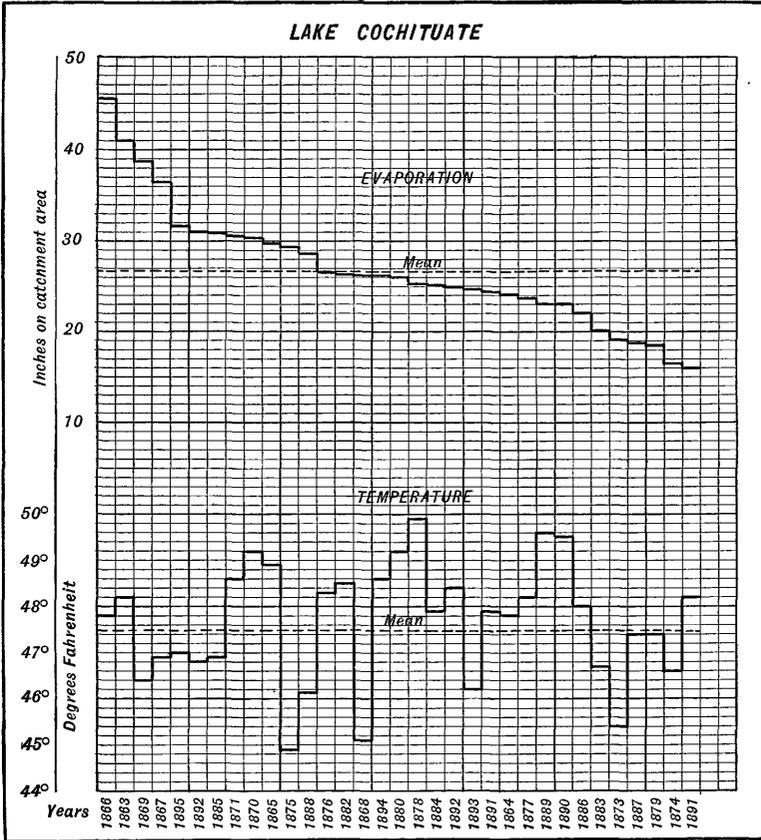


FIG. 9.—Diagram showing the relation between evaporation and temperature in the Lake Cochituate Basin, the years being arranged according to the amount of evaporation.

On fig. 10 the relation between precipitation and run-off, for the Upper Hudson, has been expressed by the formula $P^2 = 84.5 R$. These diagrams (figs. 1 to 10) all show, together with many others not here published, that there is no definite relation between evaporation and mean annual temperature.

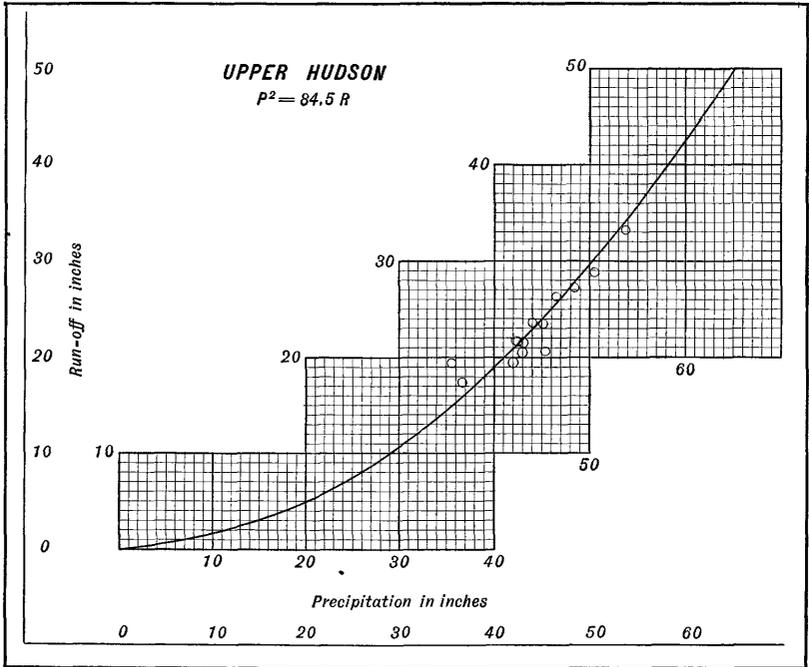


FIG. 10.—Diagram showing the relation between the precipitation and run-off in inches on the Upper Hudson River.

EXPONENTIAL FORMULA.

On fig. 11 this relation is expressed by an exponential formula, after the manner proposed by Mr. FitzGerald in his paper, "Flow of water in 48-inch pipes."^a Such a curve has the advantage that it is the best approximation possible to obtain from the given data. It will be noticed that it differs slightly from the curve of fig. 10. At 30 inches rainfall this difference amounts to about 1.3 inches of run-off.

While on the subject of exponential formulas it may be remarked that their chief advantage lies in the possibility of taking any set of data and deducing the curve which best suits the conditions.

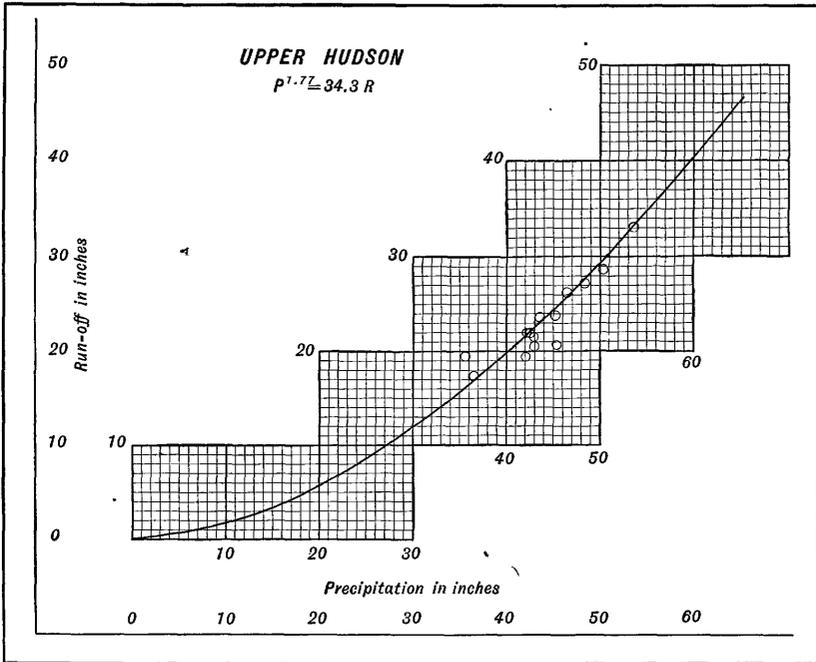


FIG. 11.—Diagram showing the relation between the precipitation and run-off in inches on the Upper Hudson River, expressed by exponential formula.

DESCRIPTION OF RUN-OFF DIAGRAMS.

Fig. 12 is a run-off diagram of Hudson and Genesee rivers, Hudson River for 1888-1901, inclusive, and Genesee River for 1890-1898,

^aTrans. Am. Soc. C. E., Vol. XXXV, p. 241.

inclusive. In preparing this and the following diagrams it is considered that if both run-off and precipitation were correctly measured the points would fall in a regular curve approximately like those shown on figs. 10 and 11. Such diagrams may therefore be taken as a criterion of the accuracy with which the observations have been made. It is easier, however, to measure the run-off than it is to measure the precipitation, and hence when large variation occurs, as it does in these several diagrams, we may first look for it in the precipitation records. As regards the Hudson area, it has been the writer's custom to take the rainfall of the northern plateau of the State weather bureau as, on the whole, best representing the rainfall of the Upper Hudson area. With the exception of the years 1899 and 1900 the points all fall within from an inch to an inch and a half of the curve. Those two years have, however, been computed by a less accurate method than the preceding ones. It is concluded, therefore, that aside from 1899 and 1900 the curves represent the rainfall and run-off of

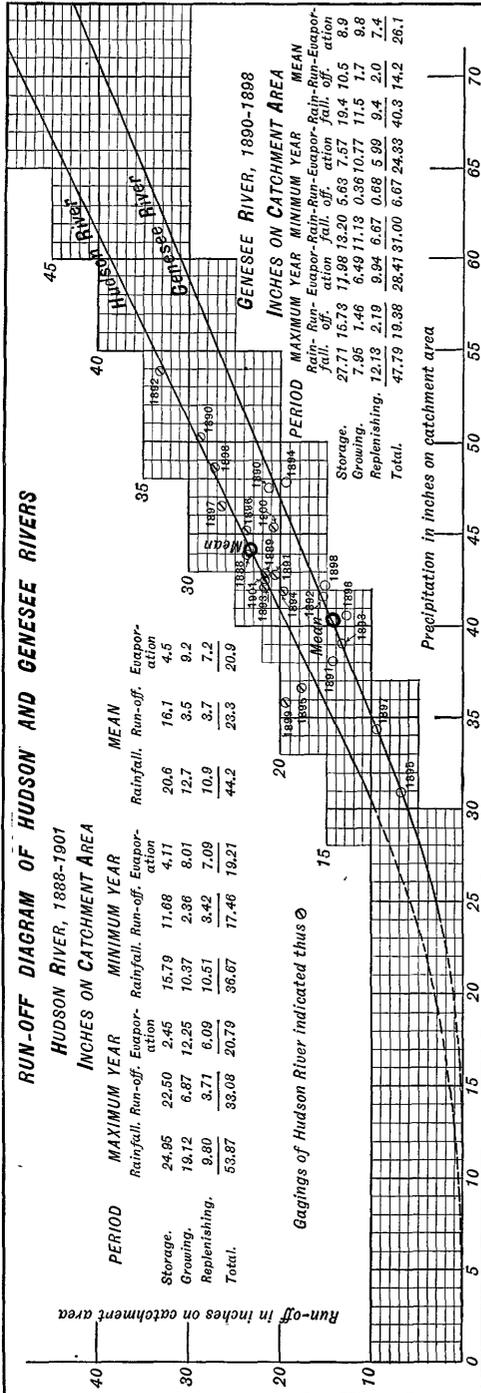


FIG. 12.—Run-off diagram of Hudson and Genesee rivers.

Hudson and Genesee rivers with considerable accuracy.

Fig. 13 shows in a similar manner a run-off diagram for Muskingum River from 1888 to 1895, inclusive.

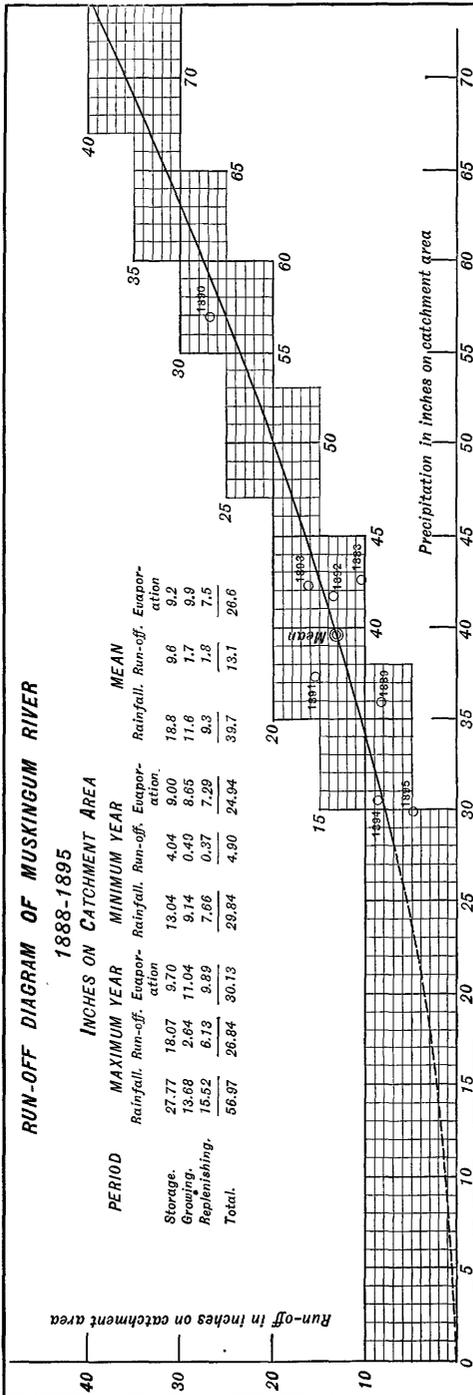


Fig. 13.—Run-off diagram of Muskingum River.

Fig. 14 is a similar diagram for Passaic River from 1877 to 1893, inclusive.

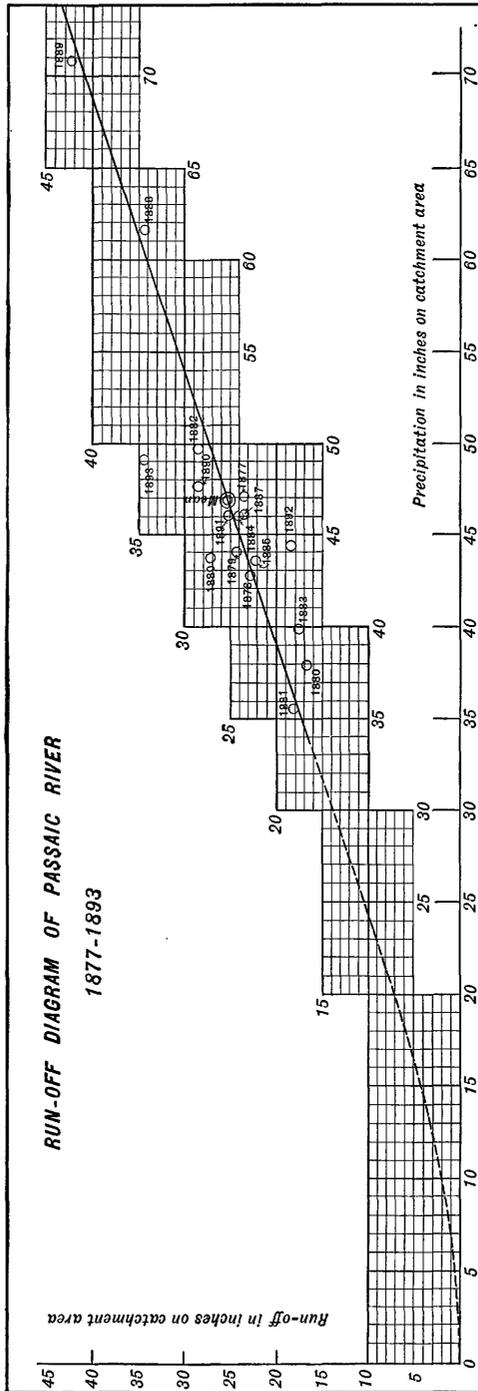


FIG. 14.—Run-off diagram of Passaic River.

Fig. 15 is a similar diagram of Sudbury River from 1875 to 1900, inclusive.

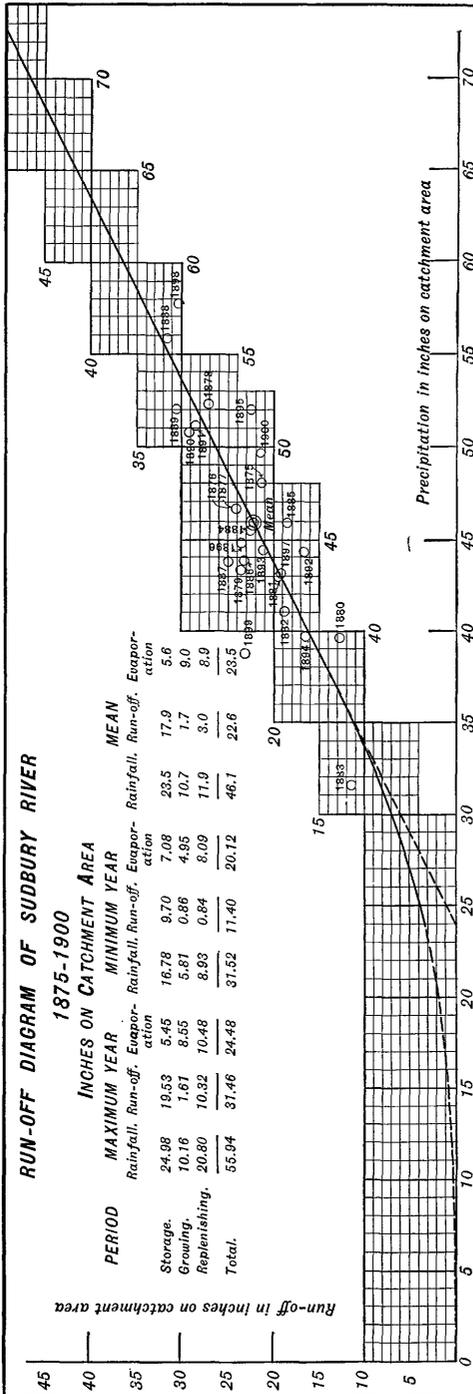


FIG. 15.—Run-off diagram of Sudbury River.

Fig. 16 is a diagram of the revised gagings of Croton River from 1877 to 1899, inclusive

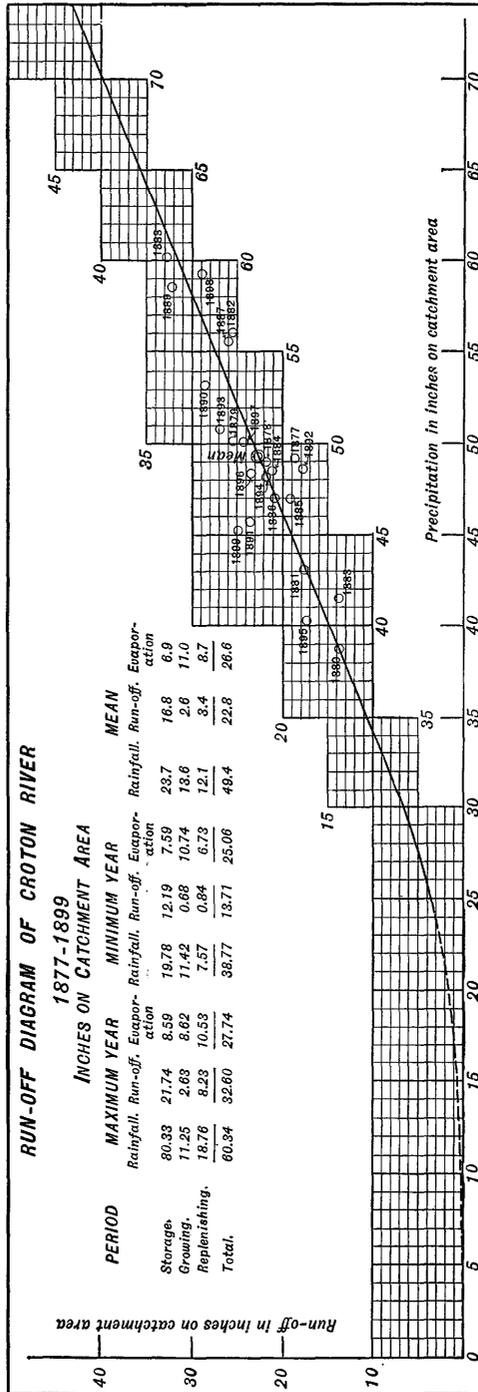


Fig. 16.—Run-off diagram of Croton River.

The maximum, minimum, and mean run-off may be obtained from the tabulations on each figure except for Passaic River.

It is evident that proceeding in the same way as for the foregoing diagrams, figs. 12-16, inclusive, diagrams may be prepared for the storage, growing, and replenishing periods, and a curve drawn from which the run-off for a given rainfall may be taken.

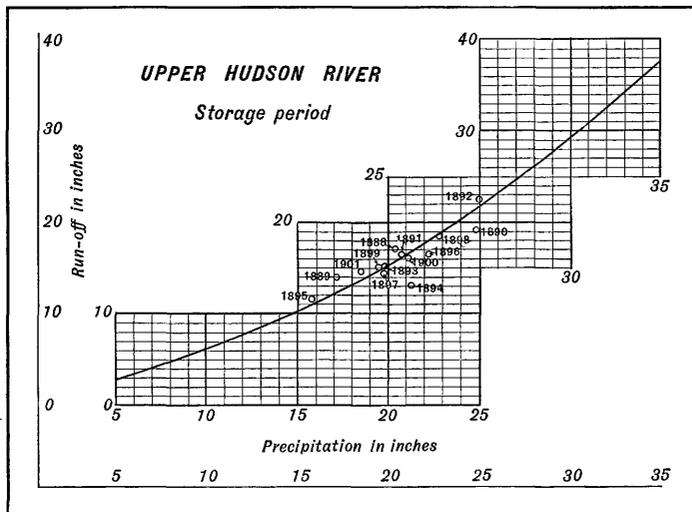


FIG. 17.—Diagram showing the relation between precipitation and run-off in the Upper Hudson River Basin during the storage period.

Fig. 17 is such a diagram for the storage period on the Upper Hudson River for the years 1888-1901, inclusive. This diagram shows that aside from the years 1890 and 1894 the run-offs of this catchment area were substantially accurate during the storage period. It is

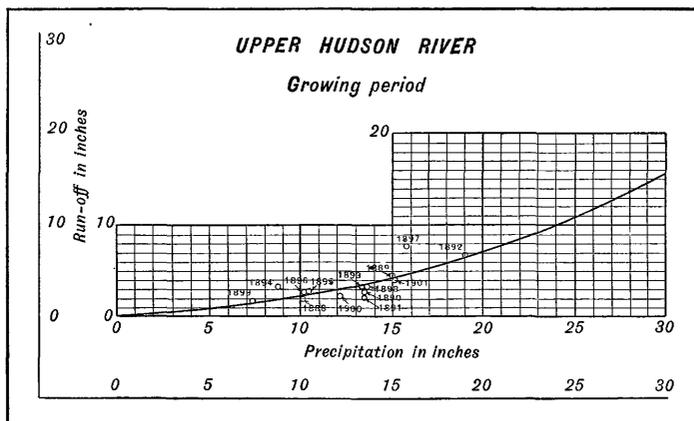


FIG. 18.—Diagram showing the relation between the precipitation and run-off in the Upper Hudson River Basin during the growing period.

probable that in these two years their accuracy may have been interfered with by ice, although just the cause is not definitely known—it may have been in the rainfall.

Fig. 18 is a similar diagram for the Upper Hudson River during the

growing period for the same years. This diagram shows that aside from 1897, the run-offs were substantially right during this period.

Fig. 19 is a similar diagram for the Upper Hudson River during the replenishing period for the same years. This diagram shows that in

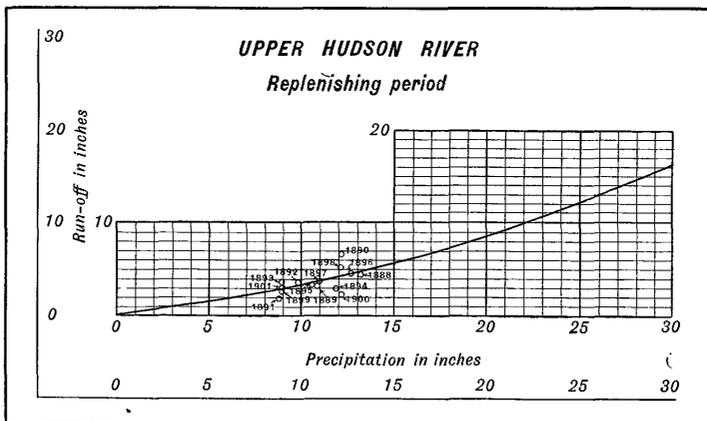


FIG. 19.—Diagram showing the precipitation and run-off in the Upper Hudson River Basin during the replenishing period.

1890 and 1900 there was a discrepancy, which, as in the previous cases, was presumably in the precipitation of that period.

Fig. 20 is a similar diagram for the storage period of Sudbury River. The observations in this case are so scattering that we may safely conclude that ice plays a very important part in the discord-

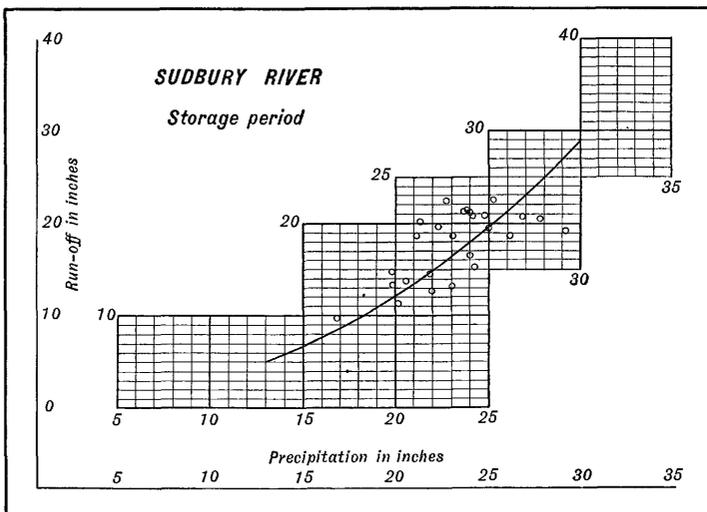


FIG. 20.—Diagram showing the relation between precipitation and run-off in the Sudbury River Basin during the storage period.

ancy of Sudbury River observations during the storage period. There is, however, during the earlier years, a lack of complete precipitation observations on the Sudbury catchment area, although it is not considered that this is a very important cause, for the reason that the

growing and replenishing periods on this stream show much better results than the storage period. The most probable assumption, therefore, seems to be the disturbing effect of ice in the storage period.

Fig. 21 is a similar diagram of Sudbury River for the growing period. With the exception of three years, the observations for this period are very reliable.

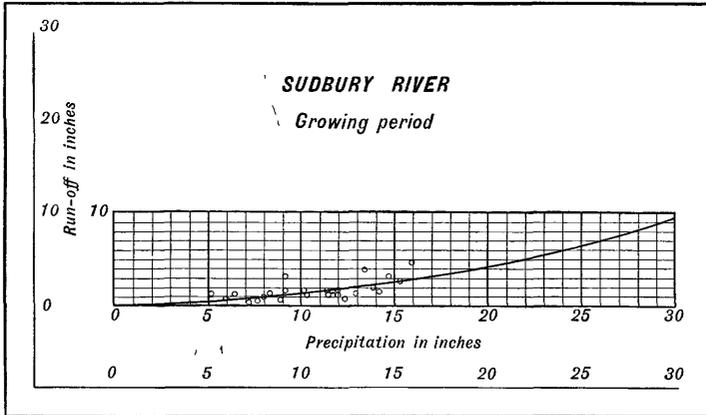


FIG. 21.—Diagram showing the relation between precipitation and run-off in the Sudbury River Basin during the growing period.

Fig. 22 is a similar diagram of Sudbury River for the replenishing period. In this case, the observations are all good except for one year.

Proceeding on similar lines, the writer prepared, several years ago,

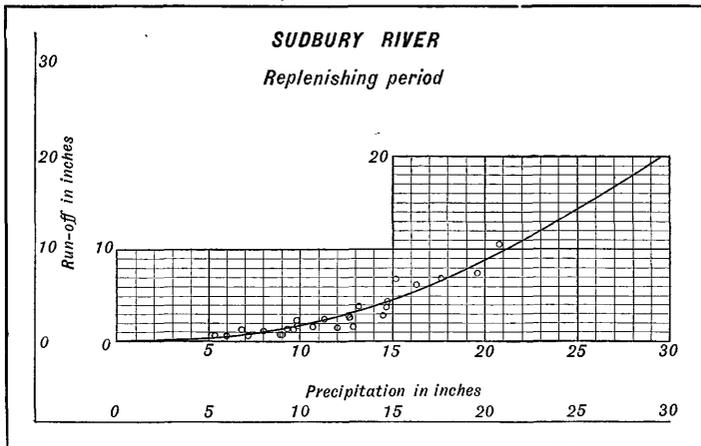


FIG. 22.—Diagram showing the relation between precipitation and run-off in the Sudbury River Basin during the replenishing period.

a series of curves, from which the monthly run-offs may be taken. But, unfortunately, owing to negative evaporation in the storage period, the individual months of that period were so discordant as to be very unsatisfactory. The writer, therefore, does not give any such

diagrams in this connection. His present view is that, for the reason stated, they can not be safely used.

Fig. 23 is a section of Mechanicville dam, over which the gagings of Hudson River have been made.

One or two general conclusions of some interest may be drawn from figs. 12-16, inclusive. For instance, taking the extreme low water as represented by the year 1895, on Muskingum River, at 4.9 inches for the whole year, with a rainfall of 29.8 inches, it is interesting to observe that in the preceding year of 1894, there was a total run-off of 8.7 inches, with a total rainfall of 30.5 inches. That is to say, the rainfall for the year 1894 was 0.7 inch greater than in 1895, but the run-off was 3.8 inches greater. This extreme difference may be ascribed to the difference in the height of ground water. In 1895, ground water stood much lower than in 1893, with the result of a lower run-off.

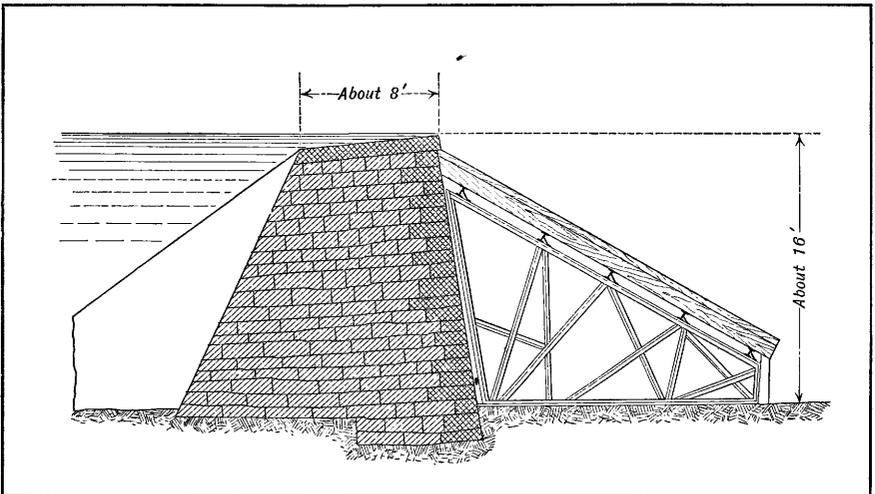


FIG. 23.—Section of Mechanicville dam.

On fig. 12, with a precipitation of 30 inches, the run-off is found to be 6 inches, while on fig. 13, with a precipitation of 30 inches, run off ordinarily may be expected to be about 8 inches. This statement is made on the assumption that the curve is drawn in a mean position, or in such a way as to give average mean results, but it should not be overlooked that Muskingum River observations are too few to draw absolute conclusions. The diagram, fig. 13, shows that there is some lack of accuracy in at least one-half of them.

Fig. 12 shows that on Hudson River, if during any year the total rainfall should sink to 30 inches, the run-off may be expected to be somewhat less than 10 inches, though the modifying effect of full or low ground water may be taken into account in reaching such conclusion. Probably there would be, due to elevation of ground water, a variation of perhaps 2 inches.

On the diagram of Passaic River, fig. 14, 30 inches of precipitation indicates 14 inches of run-off. This is very high, and shows that further study of the Passaic is needed before one can safely accept the results as entirely reliable.

On the diagram of Sudbury River, fig. 15, a precipitation of 30 inches may be expected to produce a run-off of about 7 inches, showing that this stream is, as regards run-off characteristics, very closely allied to Genesee and Muskingum rivers.

On the diagram of Croton River, fig. 16, it is also seen that 30 inches precipitation may be expected to produce a little less than 7 inches of run-off, showing also that this stream has substantially the characteristics of Genesee River.

In all of the foregoing statements as to minimum run-off, it should be understood that the actual quantity appearing in the stream as run-off from a given precipitation will vary, depending on whether ground water is high or low at the beginning of the period considered. All such statements, therefore, are necessarily approximate—they may have a plus or minus variation from the diagram of one or two inches.

SUMMARY.

In order to assist the discussion, the following summary, which includes, it is believed, the more important points of the paper, is herewith submitted:

1. There is no general expression giving accurately the relation of rainfall to run-off. The run-off of a stream is influenced by so many complex elements that the data are lacking for final conclusions. Every stream is, in effect, a law unto itself. An empirical formula may, however, be made, which will give for some streams approximately the run-off for a series of years.

2. The cause of rainfall is not very well understood, although there is one principle upon which there is no disagreement—that in order to produce rain, the temperature of the air must be cooled below the dew point.

3. The errors in rainfall measurements are so large that one may safely state that nearly all measurements are merely approximations.

4. In view of the foregoing proposition, to carry rainfall measurements out to more than one decimal place is an unnecessary refinement.

5. As a general statement the minimum rainfall may be placed at from one-half to one-fourth of the maximum.

6. It is uncertain whether rainfall is in any degree increasing.

7. In England there is sometimes an increase of rainfall with increase of elevation,^a but in the United States the areas are so large

^a See remarks of H. Somerby Wallis on this point in Monthly Weather Review for April, 1902, p. 228.

that as soon as one goes away from the influence of the ocean very frequently this peculiarity does not appear. In a very large number of cases the reverse is true.

8. Contours can not be satisfactorily drawn on a rainfall map of the State of New York until we have a larger number of stations and longer periods of observation.

9. Rainfall and run-off records are conveniently divided into storage, growing, and replenishing periods, such division facilitating computations and bringing out the salient points. A large percentage of the total water supply runs off during the storage period.

10. Assuming that a rainfall record is accurate, it should cover about thirty-five years before it can be relied upon within 2 per cent. As to a run-off record, the number of long records are as yet too few to furnish satisfactory answers to questions concerning run-off.

11. The best unit of measurement is cubic feet per second, and the next best is inches on the catchment area.

12. The run-off of streams has been generally overestimated. The minimum flow may be as low as from 0.05 to 0.1 of a cubic foot per square mile per second. Streams issuing from sand plains may show from 0.5 to 0.6 of a cubic foot per square mile per second. Generally speaking, the range will not be outside of from 0.05 to 0.5 of a cubic foot per square mile per second.

13. As regards run-off, streams may be divided into classes, in the first of which will fall streams with a maximum rainfall from 50 to 60 inches and with a maximum run-off somewhat more than one-half the rainfall, etc. They may be also classified with regard to evaporation, as will be noted further on.

14. The run-off of streams can not be satisfactorily estimated from diagrams of monthly rainfall.

15. The run-off of a stream is materially influenced by the number of lakes within its catchment area.

16. Generally speaking, maximum-discharge formulas are unsatisfactory guides and are hardly worth the trouble their use entails. Exception to this may be taken in the use of Dickens and Ryves's formulas.

17. Safe deductions can not be made from an average run-off. What is wanted is a clear statement of the minimum, together with the longest period which it may be expected to occupy.

18. There is very serious danger in using percentages.

19. The influence of the May rainfall is such that when above the normal, stream flow is likely to be well maintained during the summer.

20. As regards delivery of streams, what is wanted in a stream is as large a ground flow as possible, with small evaporation.

21. When rainfall is below the mean for several months, ground water may be expected to become continuously lower, with the result that the flow of streams will be less.

22. The run-off of streams will vary with the velocity of wind, pressure, force of vapor, etc.

23. For individual streams an exponential formula is undoubtedly the best. By its use the given data may be more closely represented than in any other manner.

24. Annual run-off diagrams may be taken as a criterion as to the accuracy with which the observations have been made.

25. When a run-off record is given, without the rainfall, the rainfall may be computed by assuming the evaporation and making a series of approximations.

26. The run-off of streams with very great difference in size of catchment areas may be experimentally compared.

27. The extreme low-water period may extend over at least two years and occasionally over three years.

28. In order to clarify the whole matter of stream gagings, what is wanted in the future is a brief, explicit statement of just how the stream was measured, thus enabling hydrologists to judge of the accuracy of the method.

29. There is considerable variation in weir measurements, due to form of weir alone. The formula for a sharp-crested weir can not be applied to any other form without large variation.

30. The several diagrams, as well as the evaporation formula, show that there is no relation between evaporation and mean annual temperature.

31. The laws of evaporation are exhibited in the chapter on "Evaporation relations," by Professor Tate.

32. Evaporation is a persistently uniform element. The tendency is to remain at about the same figure from year to year.

33. In addition to the classification of streams with reference to rainfall, those with large evaporations may be placed in a class by themselves.

34. Streams with large evaporation are, so far as known, always deforested.

35. Negative evaporation exists on all the streams included in the tables. When negative evaporation exceeds more than two consecutive months there is, generally speaking, some doubt about the accuracy of the record.

36. The ground water must be taken into account in order to understand all the peculiarities of flow. A very important effect of forests is in increasing the ground-water flow.

37. It is uncertain whether difference in geology has much influence on run-off, although it appears that porous, sandy soils do considerably affect the result. There are, however, a number of cases which indicate that it may have important influence, although an examination of the evidence shows that the theory that forests materially influence

the run-off is more reasonable than that percolation through geologic formations exercises much influence.

38. So far as present information goes there is little or no relation between topography and the run-off of streams. Deforestation appears to exercise a much more important influence.

39. It is uncertain whether forests in any way influence the quantity of rainfall.

40. The extent of forestation seems to have considerable effect on the run-off of streams, catchments with dense forests showing larger run-off for the same rainfall than those which are deforested. As a tentative proposition it may be said that the removal of forests notably decreases stream flow.

41. The effect of forests is clearly shown on Hudson River.

42. Catchment areas from which municipal water supplies are drawn should be heavily forested. This is a broad proposition merely.

43. If the Croton catchment area had growing upon it a forest from one hundred to one hundred and fifty years old there would probably be, on an average, about 5 inches more annual run-off than there is under present conditions. Nevertheless it would not be a good investment for the city of New York to reforest this area, for the reason that the gain in water supply would not be commensurate with the expense.

The foregoing summary indicates a large number of factors which in some degree affect the run-off of streams. Moreover, only the main factors have been noted; there are many more of less importance.

There is a large amount of useful information on the general subject of the relation of forests to rainfall in Bulletin No. 7 of the Forestry Division of United States Department of Agriculture—Forest Influences—which, since that bulletin is readily obtained, has not been specially referred to here.

Finally, this paper is an attempt to establish a more rational theory of the relation between rainfall and run-off of streams than has thus far obtained.

TABLES.

TABLE NO. 1.—*Muskingum River, 1888-1895, inclusive.*
[Catchment area=5,828 square miles.]

Period.	1888.			1889.			1890.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	17.16	5.17	11.99	13.52	6.02	7.50	27.77	18.07	9.70
Growing	14.31	1.77	12.54	12.12	1.24	10.88	13.68	2.64	11.04
Replenishing	11.14	3.39	7.75	10.24	.96	9.28	15.52	6.13	9.39
Year	42.61	10.33	32.28	35.88	8.22	27.66	56.97	26.84	30.13
	1891.			1892.			1893.		
Storage	16.72	12.42	4.30	20.39	9.06	11.33	25.04	14.13	10.91
Growing	13.56	1.77	11.79	16.54	3.65	12.89	8.31	1.22	7.09
Replenishing	7.08	1.37	5.71	4.81	.67	4.14	9.01	.85	8.16
Year	37.36	15.56	21.80	41.74	13.38	28.36	42.36	16.20	26.16
				1894.			1895.		
Storage				16.93	7.63	9.30	13.04	4.04	9.00
Growing				4.56	.66	3.90	9.14	.49	8.65
Replenishing				9.02	.41	8.61	7.66	.37	7.29
Year				30.51	8.70	21.81	29.84	4.90	24.94

TABLE NO. 2.—*Genesee River, 1890-1898, inclusive.*
[Catchment area = 1,070 square miles.]

Period.	1890.			1891.			1892.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	<i>a</i> 23.01	<i>b</i> 12.96	<i>b</i> 10.05	18.22	11.88	6.34	19.84	9.38	10.46
Growing	<i>a</i> 10.52	2.51	8.01	12.78	1.06	11.72	15.30	4.90	10.40
Replenishing	<i>a</i> 14.01	5.75	8.26	7.12	1.11	6.01	6.55	1.14	5.41
Year	<i>a</i> 47.54	<i>b</i> 21.22	<i>a</i> 26.32	38.12	14.05	24.07	41.69	15.42	26.27
	1893.			1894.			1895.		
Storage	20.65	<i>b</i> 11.10	<i>b</i> 9.55	27.71	15.73	11.98	13.20	5.63	7.57
Growing	9.55	<i>b</i> 1.00	<i>b</i> 8.55	7.95	1.46	6.49	11.13	.36	10.77
Replenishing	9.10	1.25	7.85	12.13	2.19	9.94	6.67	.68	5.99
Year	39.30	<i>b</i> 13.35	<i>b</i> 25.95	47.79	19.38	28.41	31.00	6.67	24.33
	1896.			1897.			1898.		
Storage	17.84	9.25	8.59	15.68	7.31	8.37	18.66	10.40	8.26
Growing	10.28	.83	9.45	11.92	1.34	10.58	14.15	2.05	12.10
Replenishing	12.56	2.72	9.84	6.79	.73	6.06	9.69	2.68	7.01
Year	40.68	12.80	27.88	34.39	9.38	25.01	42.50	15.13	27.37

a For years 1890-1892 the run-off is that of Oatka Creek, a tributary of Genesee River, and the rainfall of Oatka Creek catchment area has been taken rather than that of entire upper Genesee area.

b Approximate.

TABLE NO. 3.—*Croton River, 1868-1899, inclusive.*

[Catchment area=338.8 square miles.]

Period.	1868.			1869.			1870.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	23.24	17.25	5.99	21.89	15.75	6.14	28.42	19.01	9.41
Growing	13.64	5.75	7.89	7.77	2.01	5.76	10.59	1.56	9.03
Replenishing	14.85	11.06	3.79	15.09	4.39	10.70	10.09	.96	9.13
Year	51.73	34.06	17.67	44.75	22.15	22.60	49.10	21.53	27.57
	1871.			1872.			1873.		
Storage	19.83	9.72	10.11	14.57	10.31	4.26	22.19	18.52	3.67
Growing	16.04	2.61	13.43	14.33	3.01	11.32	8.65	1.54	7.11
Replenishing	11.95	5.65	6.30	10.75	4.38	6.37	12.58	3.20	9.38
Year	47.82	17.98	29.84	39.65	17.70	21.95	43.42	23.26	20.16
	1874.			1875.			1876.		
Storage	23.74	22.86	0.88	17.10	14.81	2.29	22.64	19.89	2.75
Growing	12.30	2.77	9.53	16.45	5.86	10.59	7.14	1.07	6.07
Replenishing	8.68	1.60	7.08	10.33	3.41	6.92	10.11	1.35	8.76
Year	44.72	27.23	17.49	43.88	24.08	19.80	39.89	22.31	17.58
	1877.			1878.			1879.		
Storage	17.49	12.36	5.13	20.99	14.19	6.80	25.17	20.81	4.36
Growing	13.17	.96	12.21	11.29	2.57	8.72	18.09	2.63	15.46
Replenishing	18.46	5.49	12.97	16.72	5.01	11.71	6.96	1.88	5.08
Year	49.12	18.81	30.31	49.00	21.77	27.22	50.22	25.32	24.90
	1880.			1881.			1882.		
Storage	19.78	12.19	7.59	24.53	14.79	9.74	27.91	16.85	11.06
Growing	11.42	.68	10.74	9.61	1.95	7.66	9.03	2.06	6.97
Replenishing	7.57	.84	6.73	8.96	.97	7.99	19.10	6.21	12.89
Year	38.77	13.71	25.06	43.10	17.71	25.39	56.04	25.12	30.92
	1883.			1884.			1885.		
Storage	19.03	11.37	7.66	24.81	16.85	7.96	21.86	15.36	6.50
Growing	12.10	1.09	11.01	15.72	2.34	13.38	12.89	.88	12.01
Replenishing	10.41	1.28	9.13	8.01	1.87	6.14	12.23	2.92	9.31
Year	41.54	13.74	27.80	48.54	21.06	27.48	46.98	19.16	27.82
	1886.			1887.			1888.		
Storage	25.45	18.16	7.29	23.05	16.44	6.61	30.33	21.74	8.59
Growing	11.68	1.53	10.15	24.75	6.71	18.04	11.25	2.63	8.62
Replenishing	9.82	1.23	8.59	7.78	2.60	5.18	18.76	8.23	10.53
Year	46.95	20.92	26.03	55.58	25.75	29.83	60.34	32.60	27.74

TABLE NO. 3.—*Croton River, 1868-1899, inclusive—Continued.*

Period.	1889.			1890.			1891.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	22.40	16.86	5.54	25.31	19.10	6.21	26.66	21.22	5.44
Growing	17.37	6.49	10.88	13.31	2.51	10.80	11.26	1.74	10.12
Replenishing	18.83	8.70	10.13	14.60	7.02	7.58	7.78	1.11	6.67
Year	58.60	32.05	26.55	53.22	28.63	24.59	45.70	23.47	22.23
	1892.			1893.			1894.		
Storage	22.93	12.87	10.06	27.34	21.41	5.93	23.24	15.65	7.59
Growing	15.37	2.60	12.77	12.39	1.84	10.55	7.95	1.82	6.13
Replenishing	10.30	2.31	7.99	11.08	3.51	7.57	17.05	4.41	12.64
Year	48.60	17.78	30.82	50.81	26.76	24.05	48.24	21.88	26.36
	1895.			1896.			1897.		
Storage	19.55	14.78	4.77	24.84	18.01	6.83	20.55	14.64	5.91
Growing	11.19	1.05	10.14	12.25	2.03	10.22	20.79	6.93	13.86
Replenishing	9.54	1.27	8.27	11.27	3.13	8.14	8.76	2.73	6.03
Year	40.28	17.10	23.18	48.36	23.17	25.19	50.10	24.30	25.80
				1898.			1899.		
Storage				28.81	20.08	8.73	22.66	21.38	1.28
Growing				17.17	4.83	12.34	12.19	1.57	10.62
Replenishing				13.36	3.99	9.37	10.37	1.96	8.41
Year				59.34	28.90	30.44	45.22	24.91	20.31
				Mean 1868-1876, in- clusive.			Mean 1877-1899, in- clusive.		
Storage				21.51	13.46	5.05	23.68	16.83	6.85
Growing				11.88	2.91	8.97	13.58	2.57	11.01
Replenishing				11.61	4.00	7.61	12.08	3.42	8.66
Year				45.00	23.37	21.63	49.33	22.81	26.52

TABLE NO. 4.—*Lake Cochituate, 1863-1900, inclusive.*

[Catchment area=18.9 square miles, not including catchment of Dudley Pond.]

Period.	1863.			1864.			1865.		
	Rain fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage.....	29.49	16.31	13.18	24.70	14.44	10.26	29.63	17.28	12.35
Growing.....	21.71	5.15	16.56	5.20	1.58	3.62	7.37	1.27	6.10
Replenishing.....	16.49	5.25	11.24	13.47	3.17	10.30	13.43	2.15	11.28
Year.....	67.69	26.71	40.98	43.37	19.19	24.18	50.43	20.70	29.73
	1866.			1867.			1868.		
Storage.....	22.87	9.38	13.49	27.02	16.47	10.55	23.02	16.95	6.07
Growing.....	22.13	2.94	19.19	20.67	3.34	17.33	12.49	3.22	9.27
Replenishing.....	16.31	3.26	13.05	10.98	2.43	8.55	15.65	4.76	10.89
Year.....	61.31	15.58	45.73	58.67	22.44	36.43	51.16	24.03	26.23
	1869.			1870.			1871.		
Storage.....	28.91	12.83	16.08	36.50	23.72	12.78	19.77	10.19	9.58
Growing.....	8.65	2.39	6.26	9.18	1.91	7.27	11.72	2.15	9.57
Replenishing.....	21.25	4.77	16.48	13.00	2.85	10.15	13.85	2.38	11.47
Year.....	58.81	19.99	38.82	58.68	28.48	30.20	45.34	14.72	30.62
	1872.			1873.			1874.		
Storage.....	14.51	8.88	5.63	20.00	18.51	1.49	20.76	16.23	4.53
Growing.....	19.58	2.95	16.63	11.63	2.47	9.16	12.78	3.83	8.95
Replenishing.....	14.20	5.39	8.81	13.27	4.68	8.59	4.64	1.63	3.01
Year.....	48.29	17.22	31.07	44.90	25.66	19.24	38.18	21.69	16.49
	1875.			1876.			1877.		
Storage.....	17.80	10.76	7.04	20.45	14.91	5.54	21.61	15.65	5.96
Growing.....	15.34	2.35	12.99	13.28	1.64	11.64	8.76	2.24	6.52
Replenishing.....	13.11	3.75	9.36	12.57	3.22	9.35	15.54	4.31	11.23
Year.....	46.25	16.86	29.39	46.30	19.77	26.53	45.91	22.20	23.71
	1878.			1879.			1880.		
Storage.....	23.38	19.08	4.30	19.96	16.83	3.13	18.47	8.55	9.92
Growing.....	13.74	2.07	11.67	13.95	2.05	11.90	12.06	.62	11.44
Replenishing.....	12.36	3.09	9.27	5.62	1.93	3.69	6.34	1.56	4.78
Year.....	49.48	24.24	25.24	39.53	20.81	18.72	36.87	10.73	26.14
	1881.			1882.			1883.		
Storage.....	22.23	12.74	9.49	23.10	12.39	10.71	16.62	8.31	8.31
Growing.....	8.74	1.56	7.18	6.50	.75	5.75	5.08	.16	4.92
Replenishing.....	8.85	1.25	7.60	12.35	2.39	9.96	8.53	1.62	-6.91
Year.....	39.82	15.55	24.27	41.95	15.53	26.42	30.23	10.09	20.14

TABLE NO. 4.—*Lake Cochituate, 1863-1900, inclusive*—Continued.

Period.	1884.			1885.			1886.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	24.79	15.70	9.09	22.80	11.90	10.90	24.14	18.97	5.17
Growing	12.79	1.54	11.25	11.70	.76	10.94	8.26	.57	7.69
Replenishing	5.82	1.09	4.73	12.15	3.69	9.06	11.12	1.92	9.20
Year	43.40	18.33	25.07	46.65	15.75	30.90	43.52	21.46	22.06
	1887.			1888.			1889.		
Storage	26.97	19.91	7.05	24.22	15.44	8.78	21.79	17.26	4.53
Growing	10.05	2.87	7.18	10.06	1.94	8.12	16.84	6.24	10.60
Replenishing	6.53	1.83	4.70	20.79	9.09	11.70	14.56	6.65	7.91
Year	43.55	24.61	18.94	55.07	26.47	28.60	53.19	30.15	23.04
	1890.			1891.			1892.		
Storage	23.42	17.17	6.25	27.73	28.21	-0.48	21.11	12.47	8.64
Growing	7.43	2.20	5.23	11.68	1.99	9.69	10.49	1.38	9.11
Replenishing	17.82	6.29	11.53	9.10	2.38	6.72	9.43	2.26	7.17
Year	48.67	25.66	23.01	48.51	32.58	15.93	41.03	16.11	24.92
	1893.			1894.			1895.		
Storage	22.84	12.40	10.44	21.00	10.25	10.75	20.18	11.29	8.89
Growing	11.01	1.90	9.11	7.79	1.24	6.55	11.79	1.45	10.34
Replenishing	7.58	2.51	5.07	10.94	2.04	8.90	18.66	6.17	12.49
Year	41.43	16.81	24.62	39.73	13.53	26.20	50.63	18.91	31.72
	1896.			1897.			1898.		
Storage	20.91	15.96	4.95	19.87	11.05	8.82	26.61	16.15	10.46
Growing	7.69	1.55	6.14	12.34	2.57	9.77	12.71	2.45	10.26
Replenishing	14.74	3.70	11.04	9.92	2.58	7.34	16.76	4.26	12.50
Year	43.34	21.21	22.13	42.13	16.20	25.93	56.08	22.86	33.22
				1899.			1900.		
Storage				22.31	18.38	3.93	28.30	14.09	14.21
Growing				8.16	.23	7.93	9.25	1.49	7.76
Replenishing				10.01	1.63	8.38	13.01	2.72	10.29
Year				40.48	20.24	20.24	50.56	18.30	32.26
				Mean for 5 years, 1896-1900, inclusive.			Mean for 38 years, 1863-1900, inclusive.		
Storage				23.60	15.13	8.47	23.15	14.92	8.23
Growing				10.03	1.66	8.37	11.59	2.08	9.51
Replenishing				12.89	2.98	9.91	12.38	3.32	9.06
Year				46.52	19.77	26.75	47.13	20.32	26.81

TABLE NO. 5.—*Sudbury River, 1875-1900, inclusive.*

[Catchment area, 1875-1878, inclusive=77.76 square miles; 1879-80=78.24 square miles; 1881-1890=75.2 square miles.]

Period	1875.			1876.			1877.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	19.78	14.69	5.09	21.37	20.10	1.27	23.07	18.71	4.36
Growing	15.34	2.78	12.56	12.89	1.43	11.46	9.06	1.61	7.45
Replenishing	13.11	3.76	9.35	12.62	2.61	10.01	14.64	3.68	10.96
Year	48.23	21.23	27.00	46.88	24.14	22.74	46.77	24.00	22.77
	1878.			1879.			1880.		
Storage	23.91	21.05	2.86	23.84	21.19	2.65	20.15	11.19	8.96
Growing	13.79	1.95	11.84	14.23	1.70	12.53	12.42	.83	11.59
Replenishing	14.73	4.12	10.61	5.37	.72	4.65	7.13	.67	6.46
Year	52.43	27.12	25.31	43.44	23.61	19.83	33.70	12.69	27.01
	1881.			1882.			1883.		
Storage	24.27	15.07	9.20	23.99	16.33	7.66	16.78	9.70	7.08
Growing	9.10	3.07	6.03	5.10	1.17	3.93	5.81	.86	4.95
Replenishing	9.66	1.35	8.31	11.96	1.42	10.54	8.93	.84	8.09
Year	43.03	19.49	23.54	41.05	18.92	22.13	31.52	11.40	20.12
	1884.			1885.			1886.		
Storage	27.78	20.38	7.40	21.90	14.36	7.54	24.19	20.75	3.44
Growing	11.76	1.58	10.18	11.47	1.27	10.20	8.83	.72	8.11
Replenishing	5.98	.53	5.45	12.61	2.84	9.77	10.78	1.62	9.16
Year	45.52	22.49	23.03	45.98	18.47	27.51	43.80	23.09	20.71
	1887.			1888.			1889.		
Storage	25.28	22.43	2.85	24.98	19.53	5.45	21.14	18.71	2.43
Growing	11.69	1.30	10.39	10.16	1.61	8.55	15.91	4.81	11.10
Replenishing	6.93	1.17	5.66	20.80	10.32	10.48	15.15	6.97	8.18
Year	43.80	24.90	18.90	55.94	31.46	24.48	52.20	30.49	21.71
	1890.			1891.			1892.		
Storage	24.77	20.87	3.90	29.96	25.90	4.06	23.15	13.12	10.03
Growing	8.36	1.41	6.95	11.89	1.27	10.62	11.43	1.62	9.81
Replenishing	17.71	6.94	10.77	9.30	1.25	8.05	9.81	1.82	7.99
Year	50.84	29.22	21.62	51.15	28.42	22.73	44.39	16.56	27.83

TABLE NO. 5.—*Sudbury River, 1875-1900, inclusive*—Continued.

Period.	1893.			1894.			1895.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	26.13	18.72	7.41	21.94	12.57	9.37	20.52	13.77	6.75
Growing	10.36	1.26	9.10	6.44	1.38	5.06	11.96	1.12	10.84
Replenishing	7.99	1.13	6.86	11.41	2.37	9.04	19.61	7.41	12.20
Year	44.48	21.11	23.97	39.79	16.32	23.47	52.09	22.30	29.79
	1896.			1897.			1898.		
Storage	22.30	19.64	2.66	19.88	13.23	6.65	26.81	20.65	6.16
Growing	8.13	.96	7.17	13.41	3.88	9.53	14.74	3.29	11.45
Replenishing	14.50	2.87	11.63	9.81	2.06	7.75	16.26	6.14	10.12
Year	44.93	23.47	21.46	43.10	19.17	23.93	57.81	30.08	27.73
				1899.			1900.		
Storage				22.73	22.28	0.45	29.13	19.12	10.01
Growing				7.16	.09	7.07	7.67	.46	7.21
Replenishing				8.82	.90	7.92	12.89	1.58	11.31
Year				38.71	23.27	15.44	49.69	21.16	28.53
				Mean for 5 years, 1896-1900, inclusive.			Mean for whole period, 1875-1900, inclusive.		
Storage				24.17	18.98	5.19	23.45	17.85	5.60
Growing				10.22	1.74	8.48	10.74	1.67	9.06
Replenishing				12.46	2.71	9.75	11.86	2.96	8.90
Year				46.85	23.43	23.42	46.05	22.48	23.56

TABLE NO. 6.—*Mystic Lake, 1878-1895, inclusive.*

[Catchment area=26.9 square miles.]

Period.	1878.			1879.			1880.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	25.22	18.43	6.79	19.42	16.40	3.02	17.28	9.94	7.94
Growing	13.65	2.37	11.28	11.85	2.21	9.64	12.36	1.72	10.64
Replenishing	13.83	3.02	10.81	5.13	1.27	3.86	6.02	1.25	4.77
Year	52.70	23.82	28.88	36.40	19.88	16.52	35.66	12.31	23.35
	1881.			1882.			1883.		
Storage	23.16	14.02	9.14	22.69	12.47	10.22	16.24	7.41	8.83
Growing	10.11	3.27	6.84	5.49	1.33	4.11	5.29	1.04	4.25
Replenishing	7.85	1.10	6.75	12.03	1.50	10.53	8.93	.99	7.94
Year	41.12	18.39	22.73	40.21	15.35	24.86	30.46	9.44	21.02
	1884.			1885.			1886.		
Storage	24.21	16.57	7.64	21.35	11.03	10.32	24.47	20.82	3.65
Growing	13.21	2.03	11.18	12.35	1.87	10.48	8.49	1.21	7.28
Replenishing	5.40	.85	4.55	13.25	3.43	9.82	9.87	1.58	8.29
Year	42.82	19.45	23.37	46.95	16.33	30.62	42.83	23.61	19.22
	1887.			1888.			1889.		
Storage	25.83	17.44	8.39	24.03	16.09	7.94	23.17	17.47	5.70
Growing	14.24	3.49	10.75	10.66	1.77	8.89	15.69	5.27	10.42
Replenishing	7.59	1.76	5.83	20.37	9.09	11.28	13.94	4.76	9.18
Year	47.66	22.69	24.97	55.06	26.95	28.11	52.80	27.50	25.90
	1890.			1891.			1892.		
Storage	24.35	18.66	5.69	27.67	26.79	0.88	21.35	11.58	9.77
Growing	9.28	2.81	6.47	11.49	1.87	9.62	11.55	2.32	9.23
Replenishing	13.92	5.14	8.78	9.50	1.55	7.94	8.47	2.08	6.39
Year	47.55	26.61	20.94	48.66	30.22	18.44	41.37	15.98	25.39
	1893.			1894.			1895.		
Storage	23.09	15.42	7.67	21.34	11.14	10.20	18.50	10.34	8.16
Growing	9.55	2.20	7.35	6.69	1.78	4.91	13.41	1.82	11.59
Replenishing	8.36	1.67	6.69	11.59	1.85	9.74	18.50	4.09	14.41
Year	41.00	19.29	27.71	39.62	14.77	24.85	50.41	16.25	34.16

TABLE No. 7.—*Neshaminy Creek, 1884-1899, inclusive.*

[Catchment area=139.3 square miles.]

Period.	1884.			1885.			1886.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	25.77	25.61	0.16	20.13	17.85	2.28	26.61	21.45	5.16
Growing	13.71	1.85	11.86	10.25	1.08	9.17	12.67	1.87	10.80
Replenishing	7.05	.45	6.60	11.22	1.73	9.49	7.60	.66	6.94
Year	46.53	27.91	18.62	41.60	20.66	20.94	46.88	23.98	22.90
	1887.			1888.			1889.		
Storage	21.88	15.92	5.96	26.48	21.17	5.31	22.32	13.44	8.88
Growing	19.26	4.44	14.82	11.83	1.01	10.82	22.42	10.00	12.42
Replenishing	7.59	1.03	6.56	14.18	6.02	8.16	22.18	12.37	9.81
Year	48.73	21.39	27.34	52.49	28.20	24.29	66.92	35.81	31.11
	1890.			1891.			1892.		
Storage	22.06	14.85	7.21	23.48	17.74	5.74	22.55	15.01	7.54
Growing	14.28	2.15	12.13	15.90	2.53	13.37	11.58	1.31	10.27
Replenishing	10.23	3.33	6.90	8.06	2.33	5.70	10.13	1.94	8.19
Year	46.57	20.33	26.24	47.46	22.65	24.81	44.26	18.26	26.00
	1893.			1894.			1895.		
Storage	22.16	18.52	3.64	26.68	18.16	8.52	20.97	15.84	5.13
Growing	12.21	1.70	10.51	8.95	1.82	7.13	11.41	2.07	9.34
Replenishing	11.07	3.74	7.33	16.45	6.12	10.33	6.21	.24	5.97
Year	45.44	23.96	21.48	52.08	26.10	25.98	38.59	18.15	20.44
				1896.			1897.		
Storage				20.52	11.54	8.98	19.23	10.60	8.68
Growing				10.80	1.65	9.15	17.70	6.50	11.20
Replenishing				12.65	3.41	9.24	9.06	2.11	6.95
Year				43.97	16.60	27.37	46.04	19.21	26.83
				1898.			1899.		
Storage				25.68	16.87	8.81	23.09	20.50	2.59
Growing				12.34	1.69	10.65	9.41	1.76	7.65
Replenishing				12.80	3.33	9.47	10.91	1.96	8.95
Year				50.82	21.89	28.93	43.41	24.22	19.19

TABLE NO. 8.—*Perkiomen Creek, 1884-1899, inclusive.*

[Catchment area=152 square miles.]

Period.	1884.			1885.			1886.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	25.25	25.19	0.06	20.47	15.29	5.18	26.03	19.74	6.29
Growing	15.53	4.07	11.46	9.83	1.68	8.15	11.76	3.35	8.41
Replenishing	7.54	1.59	5.95	9.49	2.38	7.11	9.00	2.02	6.98
Year	48.32	30.85	17.47	39.79	19.35	20.44	46.79	25.11	21.68
	1887.			1888.			1889.		
Storage	21.63	14.66	6.97	27.48	19.67	7.81	22.99	14.28	8.71
Growing	17.26	4.26	13.00	12.42	2.17	10.25	23.38	10.02	13.36
Replenishing	6.70	1.45	5.25	14.18	7.40	6.78	20.45	11.81	8.64
Year	45.59	20.37	25.22	54.08	29.24	24.84	66.82	36.11	30.71
	1890.			1891.			1892.		
Storage	24.68	18.15	6.53	22.89	17.35	5.54	23.64	15.89	7.75
Growing	14.95	3.11	11.24	18.32	3.25	15.07	11.06	2.38	8.68
Replenishing	10.31	4.52	5.79	8.15	2.69	5.46	9.33	2.66	6.67
Year	49.34	25.78	23.56	49.36	23.29	26.07	44.03	20.93	23.10
	1893.			1894.			1895.		
Storage	22.16	17.21	4.95	24.37	15.77	8.60	23.22	15.51	7.71
Growing	12.20	1.82	10.38	8.77	2.05	6.72	10.88	1.32	9.56
Replenishing	10.18	3.33	6.85	15.40	5.18	10.22	6.25	.75	5.50
Year	44.54	22.36	22.18	48.54	23.00	25.54	40.35	17.58	22.77
				1896.			1897.		
Storage				19.99	10.26	9.73	20.00	12.37	7.63
Growing				15.05	2.83	12.22	13.69	3.08	10.61
Replenishing				14.62	4.19	10.43	10.07	2.26	7.81
Year				49.66	17.28	32.38	43.76	17.71	26.05
				1898.			1899.		
Storage				24.24	15.74	8.50	22.79	20.49	2.30
Growing				9.98	1.39	8.59	14.12	2.46	11.66
Replenishing				13.85	3.90	9.95	11.36	4.01	7.35
Year				48.07	21.03	27.04	48.27	26.96	21.31

TABLE No. 9.—*Tohickon Creek, 1884-1898, inclusive.*

[Catchment area=102.2 square miles.]

Period.	1884.			1885.			1886.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	26.06	27.27	-1.21	21.86	19.45	2.41	28.54	27.79	0.75
Growing	17.52	6.53	10.99	11.31	1.54	9.77	11.10	2.27	8.83
Replenishing	7.97	1.35	6.62	10	2.94	7.06	9.05	2.04	7.01
Year	51.55	35.15	16.40	43.17	23.93	19.24	48.69	32.10	16.59
	1887.			1888.			1889.		
Storage	21.60	18.44	3.16	28.52	27.37	1.15	25.13	17.82	7.31
Growing	19.19	4.80	14.39	12.96	1.99	10.97	23.90	12.45	11.45
Replenishing	6.71	.91	5.80	16.04	10.14	5.90	21.34	13.70	7.64
Year	47.50	24.15	23.35	57.52	39.50	18.02	70.37	43.97	26.40
	1890.			1891.			1892.		
Storage	25.09	19.01	6.08	23.07	20.23	2.84	23.43	19.76	3.67
Growing	15.49	2.54	12.95	19.77	4.99	14.78	11.22	1.52	9.70
Replenishing	10.20	5.45	4.75	7.16	2.03	5.13	10.65	3.47	7.18
Year	50.78	27	23.78	50	27.25	22.75	45.30	24.75	20.55
	1893.			1894.			1895.		
Storage	22.82	22.05	0.77	27.04	21.65	5.39	21.35	19.91	1.44
Growing	14.82	2.10	12.72	6.95	.84	6.11	12.45	1.46	10.99
Replenishing	11.31	4.06	7.25	17.63	8.11	9.52	6.63	.28	6.35
Year	48.95	28.21	20.74	51.62	30.60	21.02	40.43	21.65	18.78
	1896.			1897.			1898.		
Storage	21.69	12.30	9.39	20.82	13.93	6.89	26.40	21.20	5.20
Growing	13.76	2.91	10.85	17.32	5.12	12.20	10.87	1	9.87
Replenishing	12.53	4.52	8.06	8.78	1.98	6.80	13.80	5.19	8.61
Year	48.03	19.73	28.30	46.92	21.03	25.89	51.07	27.39	23.68

TABLE NO. 10.—*Hudson River, 1888-1901, inclusive.*

[Catchment area=4,500 square miles.]

Period.	1888.			1889.			1890.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	20.40	17.06	3.34	17.10	14.04	3.06	24.75	19.28	5.47
Growing	10.25	2.05	8.20	15.05	4.26	10.79	13.50	2.85	10.65
Replenishing	13.27	4.53	8.74	10.81	3.41	7.40	12.10	6.81	5.29
Year	43.92	^a 23.64	20.28	^a 42.96	21.71	21.25	^a 50.35	28.94	21.41
	1891.			1892.			1893.		
Storage	20.69	16.59	4.10	24.95	22.50	2.45	19.83	15.20	4.63
Growing	13.49	2.07	11.42	19.12	6.87	12.25	13.37	3.12	10.25
Replenishing	8.78	1.90	6.88	9.80	3.71	6.09	8.98	3.59	5.39
Year	42.96	20.56	22.40	53.87	33.08	20.79	42.18	21.91	20.27
	1894.			1895.			1896.		
Storage	21.37	13.18	8.19	15.79	11.68	4.11	22.17	16.52	5.65
Growing	8.73	3.20	5.53	10.37	2.36	8.01	10.25	2.53	7.72
Replenishing	11.87	2.99	8.88	10.51	3.42	7.09	12.79	4.58	8.21
Year	41.97	19.37	22.60	36.67	17.46	19.21	45.21	23.62	21.58
	1897.			1898.			1899.		
Storage	19.77	14.60	5.17	22.80	18.61	4.19	19.48	15.15	4.33
Growing	15.80	7.79	8.01	13.52	3.24	10.28	7.40	1.63	5.77
Replenishing	10.94	3.80	7.14	12.19	5.27	6.92	8.91	2.76	6.15
Year	46.51	26.19	20.32	48.51	27.12	21.39	35.79	19.54	16.25
				1900.			1901.		
Storage				21.13	16.12	5.01	18.47	14.84	3.63
Growing				12.11	2.30	9.81	15.09	4.02	11.07
Replenishing				12.17	2.25	9.92	9.02	3	6.02
Year				45.41	20.67	24.74	42.58	21.86	20.72

^a Approximate.

TABLE NO. 11.—*Pequannock River, 1891-1899, inclusive.*

[Catchment area=63.7 square miles.]

Period.	1891.			1892.			1893.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	26.78	17.49	9.29	19.54	18.11	1.43	24.70	23.62	1.08
Growing	12.52	2.21	10.31	12.83	3.46	9.37	13.02	2.53	10.49
Replenishing	7.23	2.97	4.26	9.17	2.23	6.94	10.72	4.44	6.28
Year	46.53	22.67	23.86	41.54	23.80	17.74	48.44	30.59	17.85
	1894.			1895.			1896.		
Storage	20.29	18.59	1.70	19.69	18.08	1.61	25.62	19.29	6.33
Growing	5.81	2.20	3.61	10.07	1.66	8.41	13.51	3.47	10.04
Replenishing	16.33	8.33	8	8.16	1.37	6.79	14.52	7.18	7.34
Year	42.43	29.12	13.31	37.92	21.11	16.81	53.65	29.94	23.71
	1897.			1898.			1899.		
Storage	21.05	17.57	3.48	27.29	22.74	4.55	22.29	21.95	0.34
Growing	21.31	8.10	13.21	12.24	2.48	9.76	12.57	1.88	10.69
Replenishing	9.50	2.83	6.67	13.48	3.54	9.94	10.96	2.74	8.52
Year	51.86	28.50	23.36	53.01	28.76	24.25	45.82	26.57	19.55

TABLE NO. 12.—*Connecticut River, 1872-1885, inclusive.*

[Catchment area=10,234 square miles.]

Period.	1872.			1873. ^a			1874. ^a		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-fall.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	14.92	13.30	1.62	18.16	21.80	— 3.64	23.08	23.04	0.04
Growing	18.96	6.20	12.67	10.11	2.71	7.40	14.37	6.62	7.75
Replenishing	12.42	6.64	5.78	15.04	5.22	9.82	7.76	2.15	5.61
Year	46.30	26.23	20.07	43.31	29.73	13.58	45.21	31.81	13.40
Period.	1875.			1876. ^a			1877.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-fall.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	17.51	15.47	2.04	22.50	24.74	— 2.24	18.09	12.68	5.41
Growing	14.55	3.80	10.75	12.51	3.35	9.16	14.00	2.91	11.09
Replenishing	11.36	3.60	7.76	10.57	2.28	8.29	13.08	5.27	7.81
Year	43.42	22.87	20.55	45.58	30.37	15.21	45.17	20.86	24.31
Period.	1878.			1879.			1880.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-fall.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	21.88	18.02	3.86	23.19	21.49	1.70	18.29	14.78	3.51
Growing	13.59	3.45	10.14	16.07	2.92	13.15	11.82	2.45	9.37
Replenishing	10.56	3.06	7.50	9.48	2.93	6.55	11.58	2.62	8.96
Year	46.03	24.53	21.50	48.74	27.34	21.40	41.69	19.85	21.84
Period.	1881.			1882.			1883.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-fall.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage	20.83	16.02	4.81	^b 20.50	12.14	8.36	^b 12.85	8.73	4.12
Growing	11.30	2.93	8.37	^b 11.45	3.35	8.10	^b 13.50	2.51	10.99
Replenishing	11.38	3.39	7.99	^b 6.50	2.17	4.33	^b 6.20	1.37	4.83
Year	43.51	22.34	21.17	38.45	17.66	20.79	32.55	12.61	19.94
Period.				1884.			1885.		
	Rain-fall.	Run-off.	Evapo-ration.	Rain-fall.	Run-fall.	Evapo-ration.	Rain-fall.	Run-off.	Evapo-ration.
Storage				21.42	20.20	1.22	18.58	13.63	4.95
Growing				12.14	2.79	9.35	14.82	3.20	11.62
Replenishing				8.51	2.61	5.90	11.76	5.61	6.15
Year				42.07	25.60	16.47	45.16	22.44	22.72

^aNot included in mean.^bRainfall computed, approximate.

TABLE NO. 13.—Mean or average rainfall, run-off, and evaporation for storage, growing, and replenishing periods for 12 streams of the United States.

Period.	Muskingum River, from 1888 to 1895, eight years. Catchment area, 5,828 square miles.			Genesee River, from 1890 to 1898, nine years. Catchment area, 1,070 square miles.			Croton River, from 1877 to 1899, twenty-three years. Catchment area, 388.8 square miles.		
	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.
Storage	18.8	9.6	9.2	19.4	10.5	8.9	23.7	16.8	6.9
Growing	11.6	1.7	9.9	11.5	1.7	9.8	13.6	2.6	11.0
Replenishing	9.3	1.8	7.5	9.4	2.0	7.4	12.1	3.4	8.7
Year	39.7	13.1	26.6	40.3	14.2	26.1	49.4	22.8	26.6

Period.	Lake Cochituate, from 1863 to 1900, thirty-eight years. Catchment area, 18.9 square miles.			Sudbury River, from 1875 to 1900, twenty-six years. Catchment area, 78.2 square miles. ^a			Mystic Lake, from 1878 to 1898, eighteen years. Catchment area, 26.9 square miles.		
	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.
Storage	23.1	14.9	8.2	23.5	17.9	5.6	22.4	15.1	7.3
Growing	11.6	2.1	9.5	10.7	1.7	9.0	10.9	2.3	8.6
Replenishing	12.4	3.3	9.1	11.9	3.0	8.9	10.8	2.6	8.2
Year	47.1	20.3	26.8	46.1	22.6	23.5	44.1	20.0	24.1

Period.	Neshaminy Creek, from 1884 to 1899, sixteen years. Catchment area, 139.3 square miles.			Perkiomen Creek, from 1884 to 1899, sixteen years. Catchment area, 152 square miles.			Tohickon Creek from 1884 to 1898, fifteen years. Catchment area, 102.2 square miles.		
	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.
Storage	23.1	17.2	5.9	23.2	16.7	6.5	24.2	20.5	3.7
Growing	13.4	2.7	10.7	13.7	3.1	10.6	14.6	3.5	11.1
Replenishing	11.1	3.2	7.9	11.1	3.8	7.3	11.3	4.4	6.9
Year	47.6	23.1	24.5	48.0	23.6	24.4	50.1	28.4	21.7

Period.	Hudson River, from 1888 to 1901, fourteen years. Catchment area, 4,500 square miles.			Pequannock River, from 1891 to 1899, nine years. Catchment area, 63.7 square miles.			Connecticut River, from 1872 to 1885, eleven years. ^b Catchment area, 10,234 square miles.		
	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.	Rain.	Run-off.	Evaporation.
Storage	20.6	16.1	4.5	23.0	19.7	3.3	18.9	15.1	3.8
Growing	12.7	3.5	9.2	12.7	3.1	9.6	13.8	3.3	10.5
Replenishing	10.9	3.7	7.2	11.1	4.0	7.1	10.3	3.6	6.7
Year	44.2	23.3	20.9	46.8	26.8	20.0	43.0	22.0	21.0

^a See explanatory matter.

^b Three years omitted from mean.

TABLE No. 14.—*Low-water periods on Muskingum River.*

[Catchment area=6,828 square miles.]

First period.				Second period.				Third period.			
Months.	Gross depth, in inches.	Evapora- tion from water surface.	Net run- off in inches.	Months.	Gross depth, in inches.	Evapora- tion from water surface.	Net run- off in inches.	Months.	Gross depth, in inches.	Evapora- tion from water surface.	Net run- off in inches.
1887.											
December	0.18	0.01	0.17								
1888.											
January	1.24	.01	1.23								
February	1.12	.01	1.11								
March	1.38	.01	1.37								
April	.80	.01	.79	1891.				1894.			
May	.45	.02	.43	May	0.45	0.02	0.43	April	0.75	0.01	0.74
June	.29	.02	.27	June	.91	.02	.89	May	.74	.02	.72
July	.81	.03	.78	July	.51	.03	.48	June	.42	.02	.40
August	.67	.03	.64	August	.35	.03	.32	July	.13	.03	.10
September	.61	.02	.59	September	.17	.03	.14	August	.11	.03	.08
October	.77	.02	.75	October	.26	.02	.24	September	.15	.03	.12
November	2.01	.01	2	November	.94	.01	.93	October	.10	.02	.08
December	.84	.01	.83	December	1.03	.01	1.02	November	.16	.01	.15
1889.											
January	1.89	.01	1.88	January	.74	.01	.73	December	.36	.01	.35
February	1.42	.01	1.41	February	2.40	.01	2.39	January	1.67	.01	1.66
March	.71	.01	.70	March	1.26	.01	1.25	February	.12	.01	.11
April	.88	.01	.87	April	1.38	.01	1.37	March	1.20	.01	1.19
May	.28	.02	.26	May	2.25	.02	2.23	April	.59	.01	.58
June	.47	.02	.45	June	2.30	.02	2.28	May	.10	.02	.08
July	.55	.03	.52	July	.75	.03	.72	June	.17	.02	.15
August	.22	.03	.19	August	.60	.03	.57	July	.21	.03	.18
								August	.11	.03	.08

TABLE NO. 15.—*Low-water periods on Genesee River.*

[Catchment area at point of gaging = 1,070 square miles; above proposed dam = 1,000 square miles.]

First period.				Second period.			
Month.	Gross depth, in inches.	Evaporation from water surface.	Net run-off, in inches.	Month.	Gross depth, in inches.	Evaporation from water surface.	Net run-off, in inches.
1894.			<i>Per cent.</i>	1896.			<i>Per cent.</i>
June.....	1.10	0.05	1.05	June.....	0.89	0.05	0.84
July.....	.14	.06	.08	July.....	.24	.06	.18
August.....	.22	.07	.15	August.....	.20	.05	.15
September.....	.98	.04	.89	September.....	.16	.03	.13
October.....	.44	.03	.41	October.....	1.74	.02	1.72
November.....	.82	.02	.80	November.....	.82	.02	.80
December.....	.61	.01	.60	December.....	.79	.01	.78
1895.				1897.			
January.....	.66	.01	.65	January.....	.78	.01	.77
February.....	.22	.01	.21	February.....	.79	.01	.78
March.....	1.94	.02	1.92	March.....	2.65	.02	2.63
April.....	2.01	.03	1.98	April.....	1.31	.03	1.28
May.....	.19	.06	.13	May.....	.99	.06	.93
June.....	.13	.06	.07	June.....	.44	.06	.38
July.....	.11	.05	.06	July.....	.46	.06	.40
August.....	.12	.04	.08	August.....	.44	.05	.39
September.....	.10	.03	.07	September.....	.18	.04	.14
October.....	.11	.02	.09	October.....	.18	.03	.15
November.....	.47	.01	.46	November.....	.37	.02	.35
December.....	1.32	.01	1.41	December.....	.95	.01	.94
1896.							
January.....	.47	.01	.46				
February.....	.91	.01	.90				
21 months ...	13.02	.65	12.37	19 months....	13.88	.64	13.24

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Progress reports may be found in the following publications: For 1888-89, Tenth Annual, Part II; for 1889-90, Eleventh Annual, Part II; for 1890-91, Twelfth Annual, Part II; for 1891-92, Thirteenth Annual, Part III; for 1893 and 1894, Bulletin No. 131; for 1895, Bulletin No. 140; for 1896, Eighteenth Annual, Part IV, WS 11; for 1897, Nineteenth Annual, Part IV, WS 15, 16; for 1898, Twentieth Annual, Part IV, WS 27, 28; for 1899, Twenty-first Annual, Part IV, 35-39; for 1900, Twenty-second Annual, Part IV, WS 47-52; for 1901, WS 65, 66, 75; for 1902, WS 82-85.